Final Report

Lifecycle Analysis of High-Global Warming Potential Greenhouse Gas Destruction

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Prepared for:
The California Air Resources Board

Prepared by
Pamela Mathis
ICF International
620 Folsom Street, Suite 200
San Francisco, CA 94107
415.677.7100

11-036

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Disclaimer

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Pamela Mathis (ICF International)

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Abstract

Currently, high-global warming potential (GWP) gases account for 3% of California's total greenhouse gas emissions, but are projected to rise to nearly 8% by 2020. Such gases include ozone-depleting substances (ODS) (e.g., chlorofluorocarbons (CFCs), hydrofluorochlorocarbons (HCFCs), halons)—as well as ODS substitutes, primarily hydrofluorocarbons (HFCs)—which are used in a wide variety of products and equipment, including refrigeration and air-conditioning (AC) equipment, building insulation, specialized fire protection equipment, and more. Using a lifecycle approach, this study assesses various end-of-life management options for reducing GHG emissions at time of disposal. In particular, current and alternative management options for reducing GHG emissions from the following sources at end-of-life (EOL) are reviewed: (1) household refrigerators/freezers; (2) other stationary refrigeration/AC equipment; (3) 30-lb. refrigerant cylinders used in the refrigeration/AC servicing sector; (4) foam insulation contained in the walls, roofs, and floor of decommissioned buildings; and (5) fire extinguishing systems and high-GWP solvents. For each alternative management scenario reviewed, the costs of reducing GHG emissions are calculated on a per-metric ton of carbon dioxide equivalent ($MTCO_2eq.$) basis.

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Executive Summary

Background

To reduce statewide greenhouse gas (GHG) emissions to 1990 levels by 2020, per the goals of the California Global Warming Solutions Act of 2006 (AB 32), the Air Resources Board (ARB) is considering policies to reduce emissions of high global warming potential (GWP) gases—including ozone-depleting substances (ODS) as well as ODS substitutes—e.g., hydrofluorocarbons (HFCs)—which are used in a wide variety of applications, from refrigeration and air-conditioning (AC) to insulating foams, fire protection equipment, solvents, and other applications. Currently, high-GWP gases account for 3% of California's total GHG emissions, but are projected to rise to nearly 8% by 2020, as these gases become increasingly adopted as alternatives for ODS being phased-out under the *Montreal Protocol on Substances that Deplete the Ozone Layer*. While a number of ARB regulations already target the reduction of high-GWP gas emissions,[1] their recovery and reuse/destruction at product/equipment end-of-life (EOL) is a possible option for providing further reductions. Given that many options exist to recover, collect, transport, and destroy high-GWP gases, this study aims to identify those management options that are most environmentally and economically effective from a lifecycle perspective.

Methods

This study assesses current (baseline) and alternative management options for reducing GHG emissions through proper recovery of high-GWP gases from five types of product/equipment at end-of-life (EOL). Specifically, the following alternative management scenarios are assessed:

1. **Foam recovery from household refrigerators/freezers:** (a) manual foam recovery by existing facilities; (b) manual foam recovery using new and existing dedicated appliance recycling (DAR) facilities; and (c) fully-automated foam recovery using new and existing DAR facilities only.
2. **Refrigerant recovery from other stationary refrigeration and air-conditioning (AC) equipment:**[2] refrigerant recovery and destruction/reclamation of (a) 10% of banks reaching EOL; (b) 50% of banks reaching EOL; and (c) 90% of banks reaching EOL.
3. **Refrigerant recovery from reusable 30-lb. refrigerant cylinders used in the refrigeration/AC servicing sector—in lieu of disposable cylinders:** replacement of disposable cylinders with refillable cylinders over a 5-year phase-in period.
4. **Recovery of foam insulation contained in decommissioned buildings**:[3] separating and recovering blowing agent from (a) 25% of construction and demolition (C&D) panel foam and (b) 50% of C&D panel foam.
5. **Recovery of fire extinguishing agent from fire protection equipment and other high-GWP solvents from stockpiles:** reclamation/ destruction of all recoverable banks contained in fire extinguishing equipment reaching EOL and from ODS stockpiles.

For each alternative management scenario reviewed, the lifecycle costs and environmental benefits are calculated (including GHG emissions avoided, ODS emissions avoided, and

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[1] Including the Refrigeration Management Program and the Regulation Concerning the Sale and Use of Small Containers of Automotive Refrigerant.

[2] Including commercial refrigeration systems covered by the RMP rule, as well as smaller (< 50 lbs) commercial refrigeration systems; and all sizes of commercial AC, residential AC, standalone refrigeration units, and vending machines.

[3] Banks reaching EOL based on Caleb Management (2010), "Developing a California Inventory for Ozone Depleting Substances (ODS) and Hydrofluorocarbon (HFC) Foam Banks and Emissions from Foams." Prepared for California Air Resources Board and California Environmental Protection Agency.

impacts on criteria air pollutants). The analysis was developed based on available literature, market research, and stakeholder input.

Results

The costs and benefits of each of the lifecycle analyses (LCAs) are presented in Table 1 for year 2020. For comparative purposes, the overall GHG emission reduction goal of AB 32 is to reduce GHG emissions by 174 million metric tons of carbon dioxide equivalents (MMTCO$_2$eq) from projected business as usual 2020 emissions of 596 MMTCO$_2$eq to 1990 levels of 422 MMTCO$_2$eq (ARB 2007).The proper disposal of high-GWP products and equipment could lead to emission reductions of nearly 10.5 MMTCO$_2$eq in 2020 (6% of the total reduction goal).

Table 1: Summary of Costs and Benefits of Potential High-GWP Emission Reduction Measures in 2020

Potential GHG Reduction Measure	Emission Reductions (MMTCO$_2$eq)			Costs (million $)[a]			Costs Effectiveness (S/MTCO$_2$eq)[a]		
	HFC/PFC	ODS	Net GHG	HFC/PFC	ODS	Total	HFC/PFC	ODS	Net GHG
Foam recovery/destruction from household refrigerators/freezers[b]	0.19	0.07	0.26	12.41	7.32	19.73	65.24	110.71	76.96
Foam recovery/destruction from building demolition (panel foam)[c]	0.00	<0.01	<0.01	0.00	0.11	0.11	-	135.93	135.93
Refrigerant recovery & reclamation/ destruction from stationary refrigeration/AC equipment[d]	8.6	1.5	10.1	18.2-50.0	4.7-12.8	22.9-62.9	2.20-5.82	3.23-8.54	2.36-6.23
Banning use of disposable 30-lb refrigerant cylinders	0.02	0.00	0.02	8.86	0.0	8.86	444.50	-	444.50
Recovery and reclamation/destruction from EOL fire extinguishing systems[e]	0.08	0.01	0.09	(0.15)-0.49	(0.03)-0.09	(0.18)-0.59	(1.83)-6.02	(4.15)-13.63	(2.01)-6.62

[a] 2020 costs are not discounted; cost streams shown throughout the analyses (i.e., 2010-2020, 2020-2050) are discounted at 5%.

[b] Assumes Scenario 1 (manual foam recovery using existing facilities).

[c] Assumes 50% participation rate.

[d] Assumes 90% compliance scenario.

[e] Additional costs and benefits are associated with ODS solvent stockpiles, but these are assumed to be fully realized in 2010.

Current federal regulations have been in place since the 1990s that require the recovery of refrigerant from refrigeration/AC equipment at the time of recycling or disposal, and also require recovery of halon fire suppressants from extinguishing systems no longer in use. However, actual compliance with these regulations is difficult to assess and enforce. Enhanced enforcement and compliance could result in emission reductions of up to 10.2 MMTCO$_2$eq annually by 2020 from these regulations already in place.

Benefits from sources strictly additional to those controlled under current regulations are projected to be small—roughly 0.3 MMTCO$_2$eq in 2020—although analytical uncertainties may significantly understate these potential savings. Sources additional to those controlled under current regulations include: foam recovery/destruction from household refrigerators/freezers; foam recovery/destruction from building demolition (panel foam); and banning the use of disposable (non-refillable) 30-lb refrigerant cylinders.

Conclusions

Emissions of high-GWP gases from the disposal of products/equipment can lead to significant GHG reductions by either bolstering/enforcing existing regulations or introducing new mechanisms. In particular, compliance with existing recovery regulations is key to ensuring GHG reductions from stationary refrigeration/AC equipment, disposable refrigerant cylinders, and fire extinguishing equipment; this could be achieved through the promotion of tradable credit/certificate systems, taxes on virgin chemical sales, rebates on the return of used high-

GWP gases for destruction/ reclamation, and/or producer responsibility schemes. No regulations currently govern the timely management of ODS stockpiles or the recovery of foam from disposed appliances or decommissioned buildings. In the near-term, HFC emission reductions beyond what is expected from current regulations can be achieved through the proper recovery of foam from refrigerators/freezers;[4] in the longer-term,[5] the recovery and destruction of high-GWP foams from decommissioned buildings will represent an opportunity for reductions—especially if the recovery of board stock and spray foams becomes technically/economically feasible.

The key findings by LCA/sector are summarized below.

- **Household refrigerators/freezers:** the recovery and destruction of refrigerator/freezer insulation foams results in net GHG savings using both manual and fully-automated recovery techniques. While foam recovery using only fully-automated DARs results in the greatest GHG savings, the most cost-effective reductions can be achieved using manual foam recovery at existing facilities ($67/MTCO$_2$eq from 2010-2020). Actual GHG savings and cost effectiveness of all scenarios may be significantly greater if less optimistic landfill conditions are at play; without bioremediation, sorption, or combustion of gases in landfills, HFC emission reductions in 2020 would be 0.48 MMTCO$_2$eq and cost $25.83/MTCO$_2$eq (undiscounted). Because high-GWP foam blowing agents are being replaced by more climate-friendly alternatives,[6] any policies aimed at reducing EOL emissions from household refrigerators/freezers should be implemented in the near-term, before the opportunity is lost.
- **Other stationary refrigeration/AC equipment:** recovery of refrigerant from stationary refrigeration/AC equipment at EOL is required by federal law, but actual compliance is difficult to assess and enforce. If additional measures are considered to bolster recovery requirements such that a 90% compliance level is achieved, significant GHG emissions can be avoided. For example, by achieving a 90% recovery rate in lieu of only 10%, the release of 433 MMTCO$_2$eq can be avoided from 2010 through 2050. Recovery at equipment EOL is most critical from residential AC, large commercial refrigeration, and commercial AC systems.
- **Disposable refrigerant cylinders:** By banning disposable (non-refillable) cylinders, an estimated 0.7 MMTCO$_2$eq can be avoided by 2050, though at significant cost (i.e., net present value [NPV] cost of $254/MTCO$_2$eq for HFCs through 2050, assuming a 5% discount rate). However, actual emission reductions and cost-effectiveness of this measure may be substantially higher if compliance with ARB's Refrigerant Management Program is low—up to 14 MMTCO$_2$eq avoided by 2050 at only $14/MTCO2eq for HFCs.
- **Building foams:** GHG emissions from building foams disposed of through building demolition or renovation were estimated to be 4.4 MMTCO$_2$eq annually in 2010. However, recovering the insulating foam from building C&D waste would be extremely labor intensive, resulting in a GHG reduction cost of up to $300/MTCO$_2$eq reduction for certain foam types, which is not considered to be economically feasible. However, one type of insulation foam, steel-faced foam insulating panels, was identified as a candidate for further cost-benefit analysis because research indicates that this foam type can be recovered more easily and that roughly 80% of C&D panels in California are already segregated due to the high value of recycled metals. Foam recovery and destruction from steel-faced panels could be added to the recycling process, resulting in HFC emission reductions of up to 1.04 MMTCO$_2$eq

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[4] GHG benefits are projected to decline beyond 2018, once the average GWP of foams contained in disposed units declines.

[5] No HFCs are projected to reach EOL in buildings until 2031.

[6] It is projected that potential GHG emission savings will peak in 2018 and gradually decline to zero by 2042.

annually by 2050, at an NPV cost of \$90/MTCO$_2$eq (assuming a 5% discount rate). The emission reductions are relatively small because steel-faced foam panels only represent 10% or less of all building foam insulation currently in place. Additionally, ODS foam panels are not expected to reach EOL in CA buildings until 2016, and HFC foam panels are not expected to reach EOL until 2031. Moreover, an optimistic scenario for BAU landfill conditions is applied in this analysis, which significantly reduces emissions in the BAU; with less favorable landfill conditions, HFC emission reductions by 2050 could be as much as 0.28 MMTCO$_2$eq annually at only \$33/MTCO$_2$eq. Pending additional research and development, other types of building foam (which represent an estimated 90% of the CA market) could become technically/ economically recoverable.[7]

- **Fire extinguishing systems and ODS solvent stockpiles:** Recovery of fire extinguishing agent from EOL equipment is required by federal law. Although actual compliance levels are difficult to ascertain, baseline compliance is believed to be high.[8] Conversely, while venting is prohibited from ODS stockpiles, no legal requirements are in place to require the recycling/reclamation/destruction of these stockpiles, such that there is a risk of eventual leakage from stored chemicals over time. Fire extinguishing agent GHG reductions of 1.4 MMTCO$_2$eq from 2010 through 2020 can be realized at a cost range of -\$2.34 (cost savings) to a net cost of \$7.93/MTCO$_2$eq of reduction, depending on whether the agent is recovered from total flooding or streaming applications, and whether the recovered agent is subsequently reclaimed or destroyed. ODS solvent stockpiles are expected to be recovered or emitted before 2020. The total reductions possible from ODS solvent stockpiles from 2010 through 2020 are 0.1 MMTCO$_2$eq at a cost of -\$1.11- \$3.75/MTCO$_2$eq. Cumulatively, reclamation or destruction of both fire extinguishing agents and ODS solvent stockpiles can result in estimated GHG savings of nearly 1.5 MMTCO$_{2e}$q from 2010 through 2020.

Recommendations

Based on research findings, the high-GWP source with the greatest potential for emission reductions is enhanced recovery of refrigerant from refrigeration/AC systems reaching EOL. Additional research could be conducted to ascertain the most effective enforcement or incentive programs to increase refrigerant recovery from equipment.

Recovery and reclamation of fire suppressant is an economic net benefit and pays for itself. Industry data indicate that these high-value fire suppressants are managed stringently, resulting in few unintended emissions. No additional research recommended.

The banning of non-refillable refrigerant cylinders would not result in significant GHG reductions, assuming compliance with existing ARB refrigerant cylinder evacuation requirements is high. It is recommended that compliance with such requirements be monitored closely to determine if additional cylinder management measures are necessary.

Recovery and destruction of refrigerator/freezer foam and building insulating foam panels results in relatively few GHG reductions at a relatively high cost per MTCO$_2$eq reduced. However, additional research into actual GHG emissions from landfilled foam should be conducted to determine if waste foam emissions are significant sources of GHGs.

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[7] It is currently estimated that the costs of recovery of board stock and spray foam from decommissioned buildings is \$300/MTCO$_2$e given the technical difficulty of foam separation and processing (BRE 2010, as reported in Caleb 2010).

[8] In the fire sector, there are established routes for managing high-GWP gases at EOL. Moreover, such gases are valuable materials and are easily recycled or reclaimed for reuse. Thus, current market conditions—in addition to environmental/legal concerns—encourage recovery and recycling at EOL.

I. LCA on Household Refrigerators and Freezers Reaching End-of-Life

I.1. Introduction

Household refrigerators and stand-alone freezers contain refrigerants and foam-blowing agents (embedded in the insulating foam) that are ozone-depleting substances (ODS) and/or potent greenhouse gases (GHGs). Although the U.S. government has phased out many of the most potent ODS through regulations, older models being disposed of today still contain ODS and/or GHG that can be released when these items are processed for recycling. To reduce ozone depletion and climate impacts, federal regulations require the recovery and reuse or proper destruction of these refrigerants at appliance end-of-life (EOL). However, foam-blowing agents can be, and typically are, shredded along with the rest of the appliance. The shredded foam, mixed with other waste components (collectively known as “auto shredder residue” or ASR), is then used as alternative daily cover (ADC) at landfills.

Shredding foam may not represent the best environmental approach to appliance disposal/recycling, as this practice can lead to significant GHG emissions (foam-blowing agents have global warming potentials (GWPs) ranging from 700 to 3,800 (IPCC 1995)). As discussed in more detail below, other recycling methods may have advantages over the business as usual (BAU) solution, which relies heavily on shredding appliances. Nevertheless, no federal or state regulations directly govern the disposal of appliance foam. In the early 1990s, the United States Environmental Protection Agency (EPA) considered such regulations, but abandoned these efforts based on economic feasibility and technical practicability.

Under the California Global Warming Solutions Act of 2006 (AB 32), the California Air Resources Board (ARB) is required to limit statewide GHG emissions to those of 1990 by 2020. To help attain the legislated emission reductions requirements, ARB has identified potential measures intended to reduce emissions of high GWP gases. Significant emissions of high GWP gases result from the release of refrigerants and foam-blowing agents commonly used in household refrigerated appliances. Therefore ARB has identified appliance recycling for further study to determine the cost and benefit of additional appliance management measures (above and beyond BAU). Specifically, potential management scenarios were researched, including the proper management of insulating foam from residential appliances at end-of-life, and destruction of the foam-blowing agent.

I.1.1. Purpose

This life cycle analysis (LCA) aims to evaluate the relative environmental benefits (emissions reductions) and incremental costs associated with different management options for the recovery and destruction of high-GWP foam at appliance disposal. Specifically, three management scenarios are examined:

- **Scenario 1:** Foam recovery and recycling of all durable goods—to be achieved using manual foam recovery techniques by existing certified appliance recyclers (CARs) in addition to the foam removal already conducted by dedicated appliance recyclers (DARs). Detailed descriptions of CARs and DARs are provided in Section I.3, Defining BAU.
    - Existing CARs perform manual recovery and bagging of foam followed by destruction of bagged foam at waste-to-energy (WTE) or municipal solid waste (MSW) facilities.

  - Existing DARs follow their BAU practices, performing manual recovery and bagging of foam followed by destruction of bagged foam at waste-to-energy (WTE) or municipal solid waste (MSW) facilities.
- **Scenario 2:** Foam recovery and recycling of all durable goods— to be achieved using manual foam recovery techniques at new and existing DARs.
  - DARs perform manual foam removal using handheld and large automated saws, followed by bagging of foam for destruction at WTE facility/MSW incinerator.
  - Seven (7) new warehouse facilities (one for each new DAR) are used to accommodate the increased load, each of which is approximately 70,000 ft^2.
- **Scenario 3:** Foam recovery and recycling of all durable goods— to be achieved using fully automated systems at new and existing DARs.
  - DARs perform foam removal using fully automated treatment in an encapsulated plant.
  - Five (5) new warehouse facilities (one for each new DAR) are used to accommodate the increased load, each of which is approximately 70,000 ft^2.

Table I-1 summarizes the participation of DARs and CARs in the BAU and the three management scenarios.

Table I-1: Summary of DAR/CAR Participation in BAU and Scenarios 1 – 3

Scenario	Engaging in Foam Recovery		Foam Recovery Technique
	# DARs	# CARs	
BAU	3	Existing CARs	Manual
1	3	Existing CARs	Manual
2	10	None	Manual
3	8	None	Fully Automated/Enclosed Facility

To assess each management scenario, lifecycle costs and emissions (GHG and in some cases criteria air pollutants) associated with foam recovery, use of specialized equipment, and transportation are evaluated.

The remainder of the report is organized as follows:

- *Section 2* provides background information about refrigerator and freezer disposal options, current regulations, and environmental impacts;
- *Section 3* describes the baseline assumptions regarding foam, metals, plastics and glass handling practices, and the established boundary for this lifecycle assessment;
- *Section 4* describes the appliance EOL management scenarios;
- *Section 5* reviews key assumptions regarding emissions avoided and associated costs;
- *Section 6* examines the incremental costs associated with each management scenario, focusing on labor, transport, energy consumption, capital, and recycling costs;
- *Section 7* analyzes the emissions associated with BAU and the emission reductions associated with each management scenario;
- *Section 8* summarizes the incremental costs and emissions reductions associated with the management scenarios, providing comparisons in \$/MTCO$_2$eq from 2011 to 2050;
- *Section 9* summarizes the major findings of the analysis; and
- *Section 10* provides recommendations and additional considerations.

I.2. Background

Each year, roughly one million household refrigerators and freezers are disposed of in the state of California. Once disposed, a refrigerator may be treated in various ways. Although a small number of units are simply abandoned by individual owners or landfilled whole, most retired units are collected for recycling by recyclers (or agents), municipalities, or appliance retailers. Some are collected by utilities that offer appliance recycling programs as part of broader demand-side management (DSM) programs.

Under Section 608 of the Clean Air Act, no ODS or ODS substitute (e.g., HFC) refrigerant may be vented to the atmosphere during the disposal of appliances (40 CFR Part 82.154(a)(1) and (f)), and universal waste (e.g., mercury), used oil, and PCBs must be removed and properly managed in compliance with federal requirements for waste handling and proper disposal (40 CFR Parts 273, 279, and 761). In addition to federal requirements, the California Department of Toxic Substances Control (DTSC) established a certification program for individuals and businesses that process major appliances for scrap, per Assembly Bill 2277 (2004). Specifically, effective January 1, 2006, only a Certified Appliance Recycler (CAR) may remove Materials that Require Special Handling (MRSH)[9] from appliances (DTSC 2007).

Following the removal of harmful materials, appliances in California can be:

- Disposed of whole at a landfill;[10]
- Disassembled by a CAR and placed in an automobile shredder with subsequent landfilling of shredder residue (including foam, plastics and glass) as ADC at landfills and recycling of metals; or
- Processed at a dedicated appliance recycling facility with destruction/reclamation of foam and recycling of metals, plastics, and glass.

Nationally, the disposal of whole units in landfills accounted for an estimated 7.5% of retired units in 2005,[11] whereas upwards of 90% were sent to automobile shredders where they were crushed and baled for metal recycling (UNEP 2005).[12]

In California, refrigerators must be recycled if the unit “contains enough metal to be economically feasible to salvage…” (California Metallic Discards Act of 1991 as codified in Cal. Pub. Res. Code Section 421709a). Metals are typically separated and recycled from disposed units[13] because of the high value of ferrous materials (about $100/ton).[14] In contrast, plastics

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[9] MRSHs include CFC, HCFC, and other non-CFC replacement refrigerants; mercury; used oil; polychlorinated biphenyls (PCBs); Di (2-ethylhexyl phthalate) (DEHP) and metal-encased capacitors; and any other material that, when removed from a major appliance, is regulated as a hazardous waste.

[10] Appliances are rarely disposed of whole in landfills for two reasons: (1) The value of the metal is sufficient incentive for scrap metal recyclers to recycle the appliance; and (2) In 1991, the California Legislature passed Assembly Bill (AB) 1760 which regulated metallic discards. AB 1760 was codified in Section 42160-42185 of the Public Resources Code, which states in Section 42170 “no solid waste facility shall accept for disposal any major appliance, vehicle, or other metallic discard which contains enough metal to be economically feasible to salvage as determined by the solid waste facility operator”.

[11] Access to appliance recyclers from rural areas may be more difficult, resulting in higher levels of appliance abandonment or landfilling whole.

[12] Based on results from a survey undertaken by the Association of Home Appliance Manufacturers (AHAM), as reported in United Nations Environment Programme (UNEP) 2005.

[13] Metals are often processed by: 1) shredding all materials, separating ferrous components for recycling, and sending other materials to a landfill; or 2) crushing all materials into tin bales that are shipped to steel mills or other facilities for further processing.

and glass have a significantly lower market value, but are also generally recycled in California. When a refrigerator is placed in an auto-shredder under the BAU, plastics and glass are typically shredded along with the metals.

Recovery of insulating foam containing ODS/high-GWP blowing agents in California is currently performed by two dedicated appliance recyclers (under contract to run appliance recycling programs for utilities). To engage in this foam recovery these recyclers receive a fee from the applicable utility in excess of the value of the metal. Additional discussion of utility fees and subsidies at DARs is included in this analysis in Section I.5.3 (Estimating Costs).

Because the blowing agents contained in the foam insulation of refrigerators and freezers can have GWP values ranging from 700 to 3,800 (IPCC 1995), the treatment of appliance foam at equipment EOL is important for avoiding the release of GHG emissions. CO_2-weighted EOL emissions associated with foam are influenced by the type of blowing agent, and whether and how the foam is recovered from the appliance.

Typically, 1% - 68% of foam blowing agent is emitted when the foam is shredded in an auto shredder during the metal separation process, with a weighted average loss of 24% (Scheutz, et al. 2007). Further foam GHG losses (estimated at 19%) occur when the shredded foam is placed in a landfill (e.g., during landfill compaction, prior to any possible emission capture through biological attenuation or landfill gas capture systems) (Fredenslund, et al. 2005). Once in a landfill, emissions can be reduced if landfill gas is recovered/treated. However, the greatest potential for emission reduction is to recover and destroy (e.g., incinerate) the foam.

Foam can be recovered from appliances in a number of ways. One approach is to mechanically extract the blowing agent for re-concentration and onward destruction using approved technologies.[15] This recovery can be done either in a full mechanical recovery plant, which requires the shredder to deal with metals, foams, plastics and glass all at the same time in order to extract the ODS (as typically operated in Europe and Japan), or in a hybrid approach of manual separation of the foam prior to mechanical separation of the blowing agent from the foam itself. Where foam can be separated and transported easily to appropriate facilities, the controls for municipal solid waste (MSW) incinerators and rotary kilns are typically sufficient to avoid the need for prior extraction of blowing agents; this may reduce the level of effort, cost, and energy consumption. Moreover, in some cases, the calorific value of the foam itself can be exploited to provide a positive energy gain (i.e., in waste-to-energy [WTE] plants). WTE plants operate at very high temperatures (1200 to 1800°F) that are able to autodestruct typical foam expansion agents found in appliance foam (Recovered Energy Inc. 2010; Covanta 2009; US EPA 1995). However, it is not known if existing WTE plants could handle all the appliance waste foam, as there is some evidence to suggest that attack from fluorinated gases (released from combusted foam) can be a problem, particularly where blowing agents are not removed prior to the incineration step. Currently, the Covanta Energy WTE facility in Stanislaus County, California is able to incinerate blocks of waste insulating foam recovered from appliances with no observable negative effects on the overall combustion system (Covanta 2009). Figure I-1 presents the possible fates of foam-blowing agents resulting from the three EOL options: (1)

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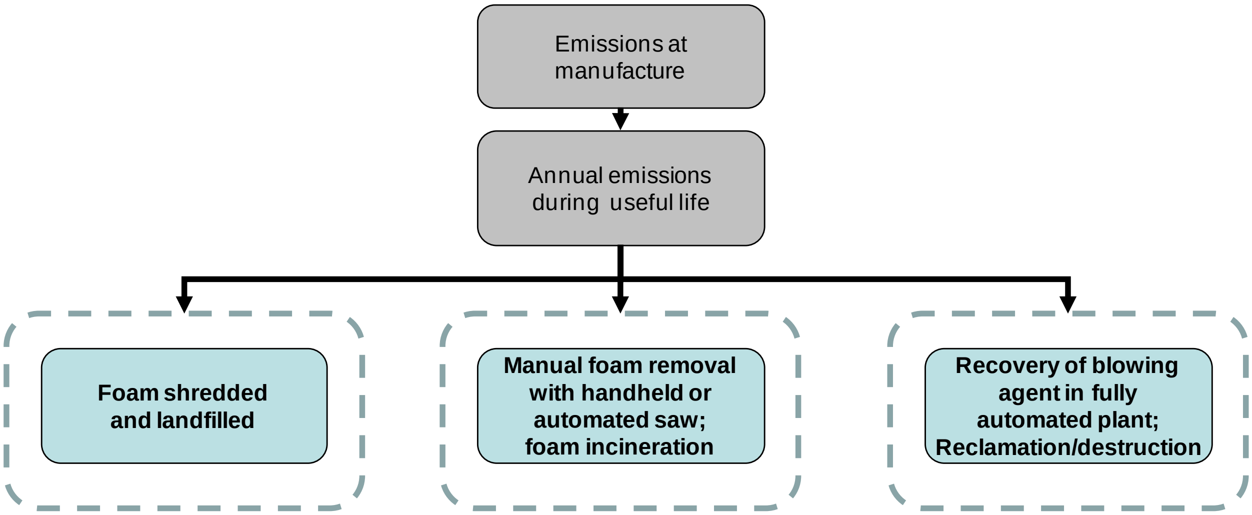
[14] Metal prices are subject to market fluctuations. However, multiple appliance recyclers and metal recyclers report that recycled steel is worth approximately $100/ton (SA Recycling 2009, 2010).

[15] Approved technologies for destroying ODS are presented in Annex II of the Report of the 15th Meeting of the Parties of the Montreal Protocol. For (dilute) ODS foam, these technologies include: municipal solid waste incineration, and rotary kiln incineration. For (concentrated) ODS refrigerants and blowing agents, approved technologies include: cement kilns, liquid injection incineration, gaseous/fume oxidation, reactor cracking, rotary kiln incineration, argon plasma arc, inductively coupled radio frequency plasma, microwave plasma, nitrogen plasma arc, gas phase catalytic dehalogenation, and superheated steam reactor.

auto shredding and landfilling, (2) manual removal and incineration of foam, and (3) recovery and destruction of blowing agent using a fully automated process (TEAP 2009).

Figure I-1: Possible Fates of Foam-Blowing Agent at End-of-Life



To reduce GHG emissions from appliances at EOL, one management option is to require the recovery and destruction of high-GWP foam and/or the recycling of all durable components. To maximize climate benefits, a technical recovery standard could be set for foam recovery (e.g., >90% of foam remaining at time of disposal must be destroyed) to ensure that best practices/technologies are used. Foam recovery from disposed appliances is already mandatory in a number of countries, including Japan and the European Union. Similarly, a number of those countries have technical standards in place for foam recovery typically specifying a minimum recovery efficiency of 90%. This analysis aims to determine whether these approaches are practicable or make economic sense in the United States, and California in particular, where the size and make-up of EOL refrigerator feedstock is somewhat unique.[16]

I.3. Defining Business as Usual (BAU)

Currently, approximately 85% of EOL refrigerators and freezers in California are transported to a Certified Appliance Recycler (CAR),[17] where the refrigerant and other harmful substances are removed, and the appliance shell is then placed in an automobile shredder. The shredded metals, plastics, and glass are sent to a recycling facility, the recovered refrigerant is sent to a reclamation facility, but the foam is typically landfilled. As shown in Figure I-2, CARs are located throughout California, with higher concentrations of facilities in the San Francisco Bay Area, near Los Angeles, and near Sacramento.

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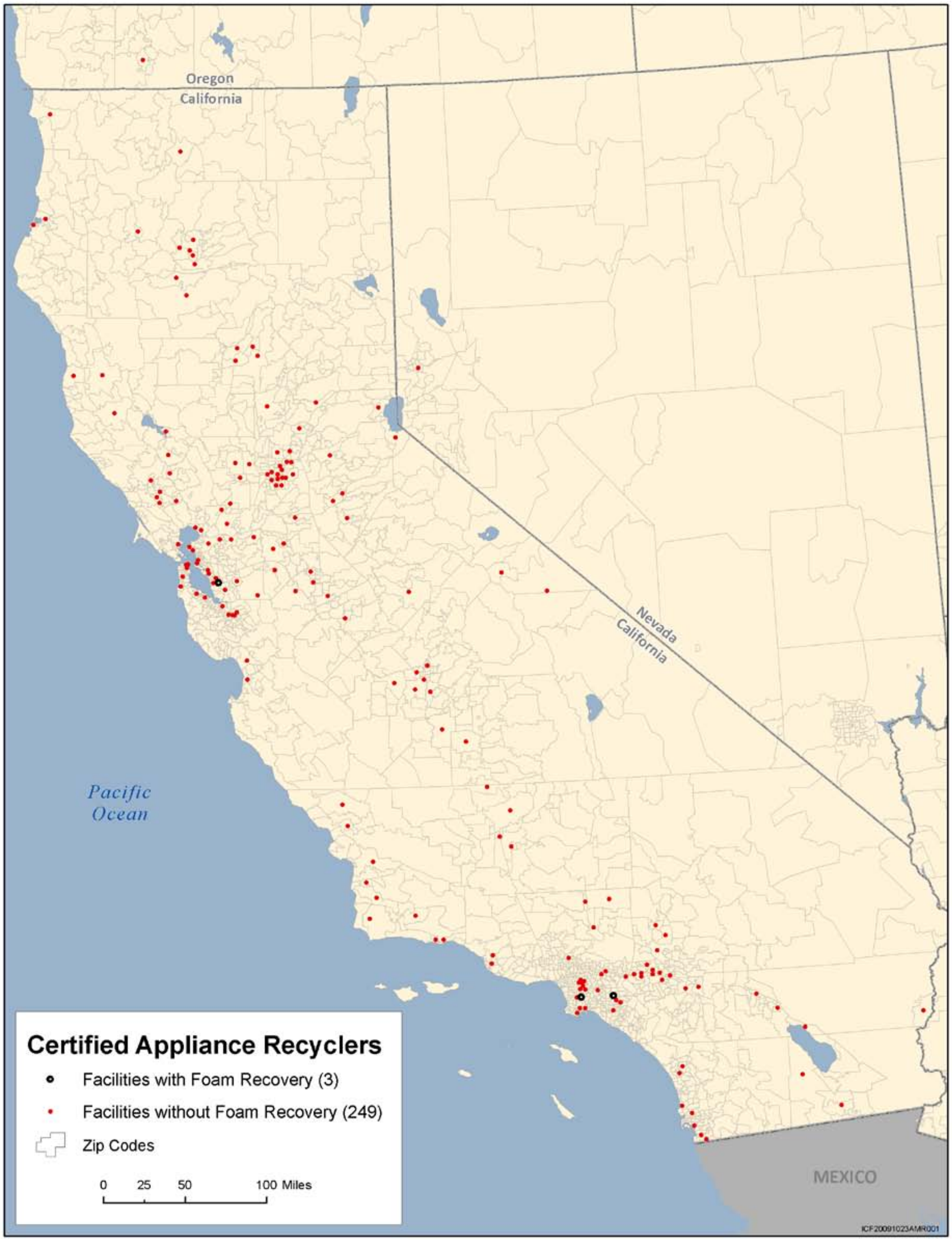
[16] Relative to other countries (e.g., EU, Japan) that have mandated the recovery of appliance foam, U.S. units are larger and contain different refrigerants and blowing agents (ICF 2008). In addition, cost implications are associated with the larger size of the U.S. and the more dispersed population centers.

[17] The California Department of Toxic Substances Control (DTSC) established a certification program for individuals and businesses that process major appliances for scrap, per Assembly Bill 2277 (2004). Specifically, effective January 1, 2006, only a Certified Appliance Recycler (CAR) may remove Materials that Require Special Handling (MRSH) from appliances (CA DTSC 2007). Although a small percent of units in California may be illegally “dumped” or abandoned, this analysis does not quantitatively address such treatment; as a result, the analysis may slightly overstate costs and benefits associated with responsible appliance disposal in California.

Figure I-2: Locations of all Certified Appliance Recyclers in CA, as of October 2009

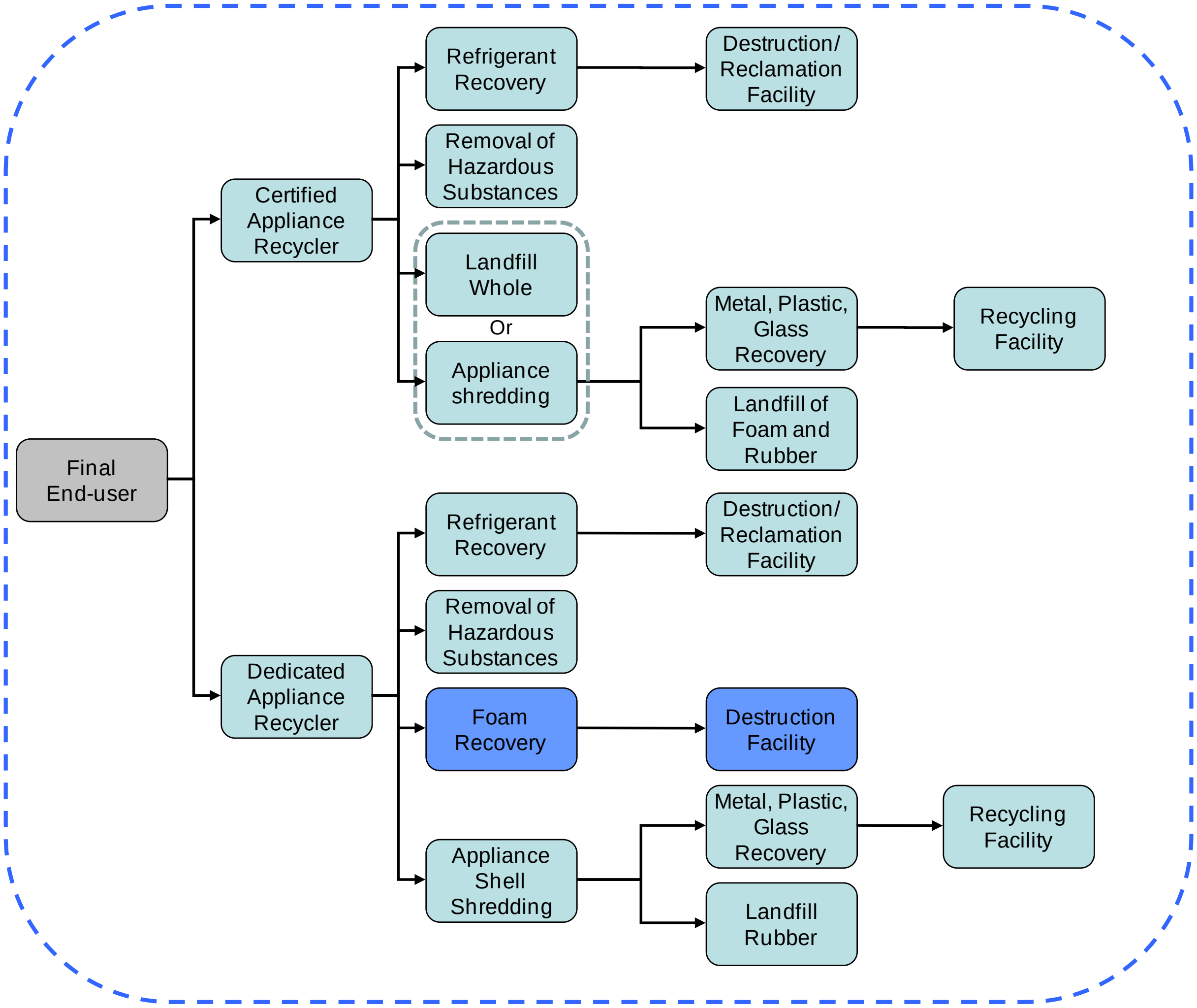


Listing of Certified Appliance Recyclers in California:
http://www.dtsc.ca.gov/HazardousWaste/Mercury/upload/Approved-CAR-List.pdf

The remaining 15% of disposed appliances in California today are handled by dedicated appliance recyclers (DARs) through utility Demand Side Management (DSM) programs that treat foam. There are currently three dedicated appliance recycling facilities in California, two owned and operated by JACO Environmental, Inc., in Fullerton and Hayward, and one owned and operated by Appliance Recycling Centers of America (ARCA), located in Compton, CA. These facilities are depicted as black outlined circles in Figure I-2. Once refrigerators and freezers are transported to these facilities, refrigerant and harmful substances are removed, and the foam is recovered manually, using handheld or automated saws and shovel-like tools. Once recovered, the foam is either (a) bagged and sent to a nearby destruction facility,[18] or (b) processed further to separate the blowing agent from the foam "fluff,"[19] with the foam-blowing agent then sent to a reclamation facility (outside of California) and the foam fluff sent to a nearby landfill; metals, plastics and glass are sent for recycling.

Figure I-3 presents these two refrigerator recycling paths.

Figure I-3: Appliance Fate in BAU



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[18] Foam is sent for destruction at waste-to-energy facilities in Stanislaus and Los Angeles Counties.

[19] This processing is performed in one dedicated appliance recycling facility in California using the Adelmann technology, a CFC-11 recovery system manufactured in Germany. The technology is estimated to be about 98% effective (i.e., 2% of the blowing agent is lost during processing). (Adelmann 2009)

This analysis assumes that approximately 1 million refrigerators and freezers reach EOL each year in California, based on 1989-2009 national sales data for refrigerators and freezers provided by the Association of Home Appliance Manufacturers (AHAM), scaled down to California based on the 10.4% CA/US household ratio, and an assumed 14-year lifetime for refrigerators (see Section I.5.1 for more detailed discussion).[20] In the BAU, 15% of appliances are handled by dedicated appliance recyclers,[21] where the foam is manually removed, either with handheld saws or with large automated saws; the remaining 85% of units are handled by CARs. Foam recovered by DARs is bagged and sent for direct incineration in a WTE facility.

The system boundary includes the transport of ODS and HFC foam containing refrigerators and freezers to CARs and DARs, as well as the handling of the foam. Because there are more CARs than DARs, the distance that appliances must travel from households to CARs is assumed to be less than the distance traveled by units going from households to DARs (see Section I.5.1 for detailed transportation assumptions). This analysis assumes 100% compliance with existing regulations[22] and focuses exclusively on the treatment of ODS and HFC foams—given that current regulations and market conditions do not already compel their recovery and proper treatment/disposal. Consequently, the following aspects are considered to be outside the project boundary: metal, plastics, and glass shredding and recycling; refrigerant recovery and destruction/reclamation; and hazardous materials removal and storage. (The project boundary does not include these activities because they are assumed to be equal in cost and benefit across all management options – BAU plus the three management scenarios explored in this lifecycle analysis.) Appliances containing hydrocarbon or other low-GWP blowing agents are also considered outside the boundary of this analysis since the release of those blowing agents does not pose a significant climate threat. Additional emission assumptions associated with the BAU are outlined in Section I.3.

I.4. Management Options

To estimate potential reductions in GHG emissions associated with appliance disposal and recycling of the foam, this analysis explores three appliance management scenarios to determine the costs and benefits of more comprehensive appliance recycling, including recovery of foam for destruction:

- **Scenario 1:** Using manual foam recovery techniques by existing certified appliance recyclers (CARs) in addition to the foam removal already conducted by dedicated appliance recyclers (DARs).
    - Existing CARs perform manual recovery and bagging of foam followed by destruction of bagged foam at waste-to-energy (WTE) or municipal solid waste (MSW) facilities.
    - Existing DARs follow their BAU practices, performing manual recovery and bagging of foam followed by destruction of bagged foam at waste-to-energy (WTE) or municipal solid waste (MSW) facilities.

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[20] It is assumed that all units sold in a given year are disposed 14 years later. For instance, all units sold in 2007 are assumed to be disposed of in 2021.

[21] ARCA, Inc., and JACO Environmental process units under contract with many utilities throughout California. Utilities known to operate appliance recycling program in the state include the City of Burbank Water and Power, the City of Palo Alto Utilities, the City of Lodi Electric Utility, Pacific Gas and Electric Company, Sacramento Municipal Utility District, San Diego Gas and Electric, Silicon Valley Power, and Southern California Edison.

[22] Actual compliance with laws requiring the recovery of refrigerant, used oil, mercury, and PCBs is believed to be less than 100%. However, because CARB is not considering regulatory changes aimed at increasing current compliance levels, the carbon footprint associated with such changes is beyond the scope of this analysis.

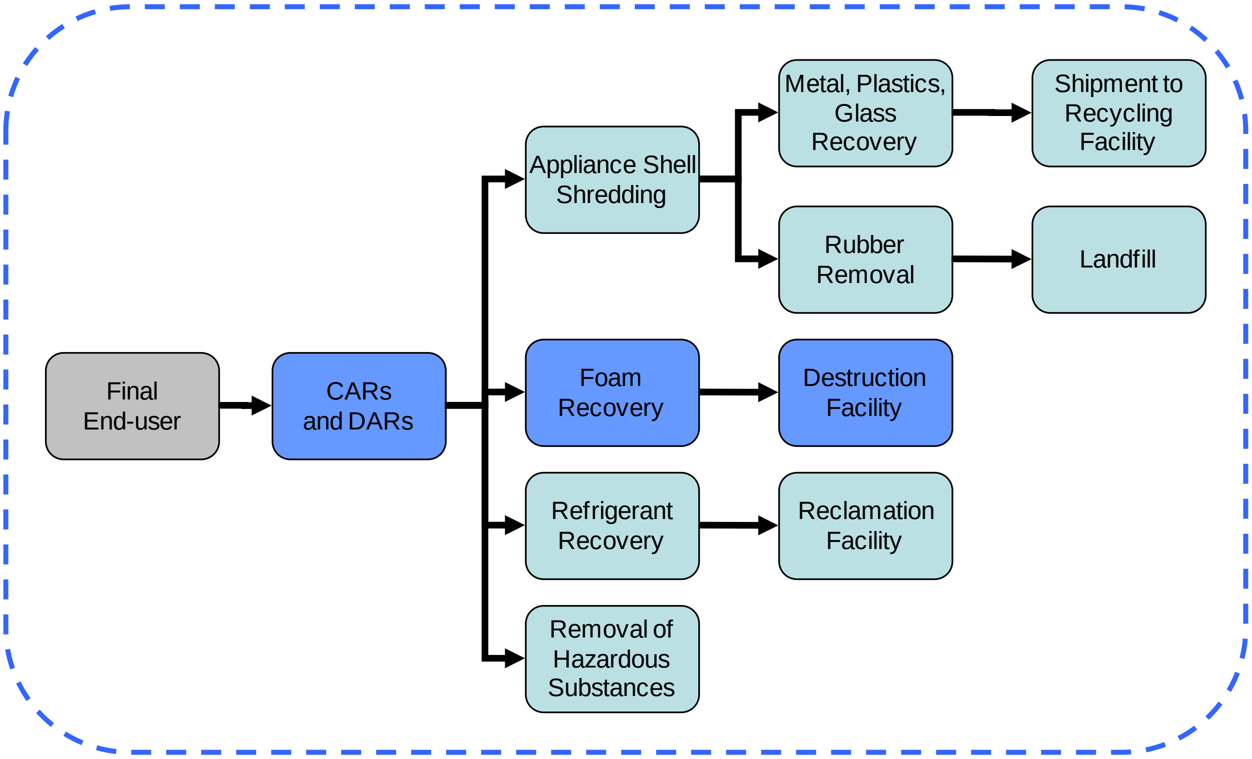
- **Scenario 2:** Using manual foam recovery techniques at new and existing DARs.
  - DARs perform manual foam removal using handheld and large automated saws, followed by bagging of foam for destruction at WTE facility/MSW incinerator.
  - Seven (7) new warehouse facilities are used to accommodate the increased load, each of which is approximately 70,000 ft^2.
- **Scenario 3:** Using fully automated systems at new and existing DARs.
  - DARs perform foam removal using fully automated treatment in an encapsulated plant; they also recycle plastics and glass.
  - Five (5) new warehouse facilities are used to accommodate the increased load, each of which is approximately 70,000 ft^2.

Each of these scenarios is described further below.

I.4.1. Scenario 1: Use All DARs and CARs

In Scenario 1, appliances are handled by both dedicated appliance recycling facilities and certified appliance recyclers. Figure I-4 depicts the chain of custody in this scenario, which is the same as that in the BAU, except that those appliances sent to the CARs would be handled similarly to those sent to DARs. It is assumed that these facilities will obtain the most basic equipment necessary to perform manual foam recovery for incineration.

Figure I-4: Fate of EOL Appliances in Scenario 1



More specific assumptions associated with this scenario are presented in Section I.4.

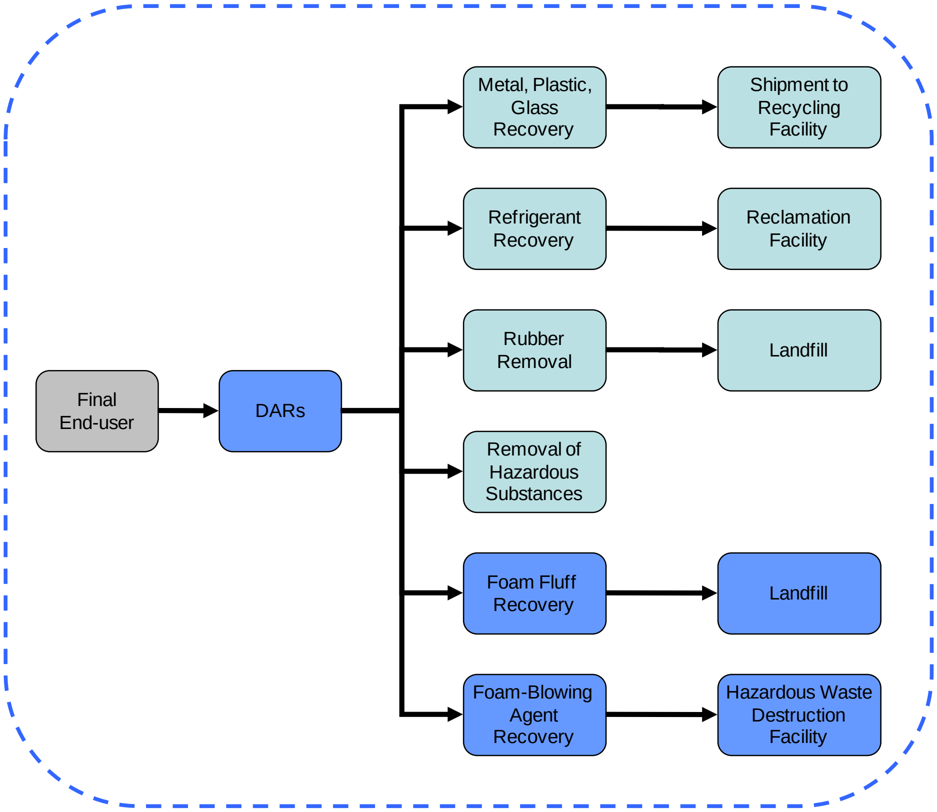
I.4.2. Scenario 2: Use Existing and New DARs with Manual Foam Removal

Under scenario 2, it is assumed that all refrigerators and freezers would be sent to dedicated appliance recycling facilities rather than to the CARs. Due to increased load at DARs, it is assumed that seven new warehouse facilities would be required to handle California's EOL appliances (each assumed to handle an annual throughput of 100,000-150,000 units). Because there are many empty and abandoned warehouses across the country and presumably in California, no new facility construction is necessary (MacPherson 2009). However, it is assumed that existing warehouses will be leased. At the seven newly acquired facilities, it is assumed that units are processed using manual foam recovery techniques, and that 50% of units are handled with automated saws while the remaining 50% are handled with handheld saws. The chain of custody in this scenario is identical to that presented in Scenario 1 but for DARs only.

I.4.3. Scenario 3: Use Existing and New DARs with Fully Automated Appliance Dismantling Machines

In scenario 3, appliances are sent to existing and newly purchased DARs, each of which is assumed to obtain a fully-automated appliance dismantling machine. Because these machines can handle a larger load than can manual operations, only five new facilities are assumed to be needed throughout the state (each assumed to handle an annual throughput of 150,000-250,000 units). At these facilities, appliances are sent through automated machines in which all components are separated, including the foam-blowing agent. The blowing agent is then reconcentrated and sent to a destruction facility approved to destroy ODS, while the remaining foam fluff is sent to a landfill. All other transport requirements are similar to scenario 2. Figure I-5 presents the chain of custody in this scenario.

Figure I-5: Fate of EOL Appliances in Scenario 3



I.5. Key Assumptions

This section outlines the key assumptions used to estimate emissions and costs associated with the three scenarios. For each scenario, the following emissions impacts are evaluated:

- Avoided direct ODS and GHG emissions due to the recovery and destruction of foam;
- Change in CO_2 emissions from energy consumption due to increased use of specialized foam recovery equipment; and
- Change in CO_2 and criteria air pollutant transport emissions due to shifted steps in the appliance disposal chain of custody.

For each of the three scenarios, the following cost impacts are evaluated:

- Change in transport labor and fuel costs due to shifted steps in the appliance disposal chain of custody;
- Change in labor time to handle foam with various removal practices;
- Change in energy consumption to handle foam with various removal practices;
- Change in operations and maintenance costs
- Change in foam fate; and,
- Capital costs from facility rental and the purchase of specialized foam removal equipment.

The remainder of this section summarizes these key assumptions. It should be noted that the following emissions and cost impacts are *not* considered in this analysis:

- Processing and recycling of metals, plastics, and glass;
- Recovery and reclamation/destruction of refrigerant; and
- Handling of other materials, including rubber and hazardous materials (i.e., PCBs, mercury, used oil).

I.5.1. Basic Assumptions

Functional Unit

In this analysis, the functional unit is one refrigerator or freezer with the composition at time of disposal as shown in Table I-2. These component weights reflect top-bottom refrigerators, which represent approximately 75% of the units disposed of today.[23]

Table I-2: Refrigerator Component Weights

Material Component	Approximate Weight (lbs.)
Foam fluff (not including blowing agent)	19
Foam Blowing Agent (rough average based on 10% blowing agent to foam ratio)	2
Plastic	20
Glass	3
Refrigerant	0.5
Metal (ferrous and non-ferrous)	140
Rubber	3
Total	188

Source: Component weights are based on assumptions by ARCA and JACO.

The total quantity of foam per unit is based on total foam volume and an assumed density of 2.0 lbs/ft^3 (ICF 2009a, 2009b, 2010; Caleb Management Services Ltd 2010; Jeffs 2010). The quantity of blowing agent per unit is dependent on the type of blowing agent. Foam emissions are calculated based on the blowing agent-specific EOL quantities presented in Table I-3.

Table I-3: Per Unit Quantity of Blowing Agent by Type

Blowing Agent Type	Ratio of Blowing Agent/Foam[a]	Quantity of Blowing Agent Remaining at EOL (lbs.)[b]
HCFC-141b	10%	2.0
HFC-134a	9%	1.7
HFC-245fa	11%	2.2

[a] The blowing agent/foam ratio for HCFC-141b is estimated to be 10%. All other ratios are adjusted by molecular weight.
[b] Quantity remaining at EOL reflect losses in first year of life (7% for HFC-134a, 4% for other BAs) and annual losses during each subsequent year of the 14 year lifetime (0.5% for HFC-134a, and 0.25% for other BAs). (UNEP 2005, IPCC 2006)
Sources: ICF 2009a, 2009b, 2009c; Jeffs 2010.

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[23] Based roughly on AHAM market saturation data from 1990, 1996, and 2001 (AHAM 2008).

Number of Disposed Units

Table I-4 presents the number of units assumed to be disposed annually in California based on national shipments data from AHAM, which is scaled down by household ratio to depict California disposal rates using an assumed 14-year appliance lifetime. For years beyond 2009, an average growth rate of 0.5% for refrigerator and freezer sales is assumed, which is consistent with the historical annual growth rate from 1989-2009 and the U.S. EPA Vintaging Model. In the BAU, it is assumed that 15% of units reaching EOL are handled by DARs, half of which are assumed to have foam removed using manual saws, and half using automated saws.

Table I-4: Projected Number of Refrigerators and Freezers Reaching EOL in California (2010-2050)

Disposal Year	Total Number of Refrigerators and Freezers Disposed[a]	Number of Units Handled by DARs in the BAU (15%)
2010	979,784	146,968
2011	979,056	146,858
2012	1,081,704	162,256
2013	1,152,944	172,942
2014	1,162,720	174,408
2015	1,198,080	179,712
2016	1,277,016	191,552
2017	1,304,576	195,686
2018	1,396,616	209,492
2019	1,388,296	208,244
2020	1,375,400	206,310
2021	1,288,664	193,300
2022	1,295,107	194,266
2023	1,301,583	195,237
2024	1,308,091	196,214
2025	1,314,631	197,195
2026	1,321,204	198,181
2027	1,327,810	199,172
2028	1,334,449	200,167
2029	1,341,122	201,168
2030	1,347,827	202,174
2031–2050	0.5% annual growth rate	

[a] These numbers do not include the approximately 40% of appliances that are given away or sold for re-use. The numbers include refrigerators containing hydrocarbon/low-GWP foams blowing agents, although such units are considered outside the boundary of this analysis. Section I.5.1 presents the assumed market transition of blowing agents.

Sources: Data on Refrigerator Shipments 1989-2007, provided to ICF by AHAM in May 2008, and updated with 2008 and 2009 data in 2010. National shipments data were scaled down according to the CA/US ratio of households, based on data from the US Census Bureau, Annual Estimates of Housing Units for the United States and States: April 1, 2000 to July 1, 2008. Available at: http://www.census.gov/popest/housing/tables/HU-EST2008-01.xls.

Market Transition of Foam-Blowing Agent

The blowing agent used in the manufacture of appliances has changed over time, as ODS have been phased out. Units being disposed today primarily contain HCFC-141b and HFC-134a blowing agents. In newly manufactured units, the most common blowing agent used today is HFC-245fa, although a small percentage has transitioned to non-GWP hydrocarbons (HCs). Table I-5 presents the market penetration of blowing agents over time. It is assumed that units containing CFC-11 have been phased out before 2010, although in reality some of these units are still being disposed of today.

Table I-5: Assumed Market Penetration of Blowing Agents in EOL Appliances, 2010-2050[a]

Disposal Year	CFC 11	HFC 134a	HCFC 141b	HFC 245fa	HCs/Low GWP Alternatives
2010	0%	2%	98%	0%	0%
2011	0%	3%	97%	0%	0%
2012	0%	4%	96%	0%	0%
2013	0%	5%	95%	0%	0%
2014	0%	6%	94%	0%	0%
2015	0%	7%	75%	18%	0%
2016	0%	4%	45%	47%	4%
2017	0%	0%	41%	50%	8%
2018	0%	0%	38%	50%	13%
2019	0%	0%	34%	49%	17%
2020	0%	0%	31%	52%	18%
2021	0%	0%	27%	55%	19%
2022	0%	0%	23%	58%	19%
2023	0%	0%	20%	60%	20%
2024	0%	0%	16%	60%	24%
2025	0%	0%	16%	56%	28%
2026	0%	0%	16%	52%	32%
2027	0%	0%	16%	48%	36%
2028	0%	0%	16%	44%	40%
2029	0%	0%	0%	56%	44%
2030	0%	0%	0%	52%	48%
2031	0%	0%	0%	48%	52%
2032	0%	0%	0%	44%	56%
2033	0%	0%	0%	40%	60%
2034	0%	0%	0%	36%	64%
2035	0%	0%	0%	32%	68%
2036	0%	0%	0%	28%	72%
2037	0%	0%	0%	24%	76%
2038	0%	0%	0%	20%	80%
2039	0%	0%	0%	16%	84%
2040	0%	0%	0%	12%	88%
2041	0%	0%	0%	8%	92%
2042	0%	0%	0%	4%	96%
2043	0%	0%	0%	0%	100%
2044–2050	0%	0%	0%	0%	100%

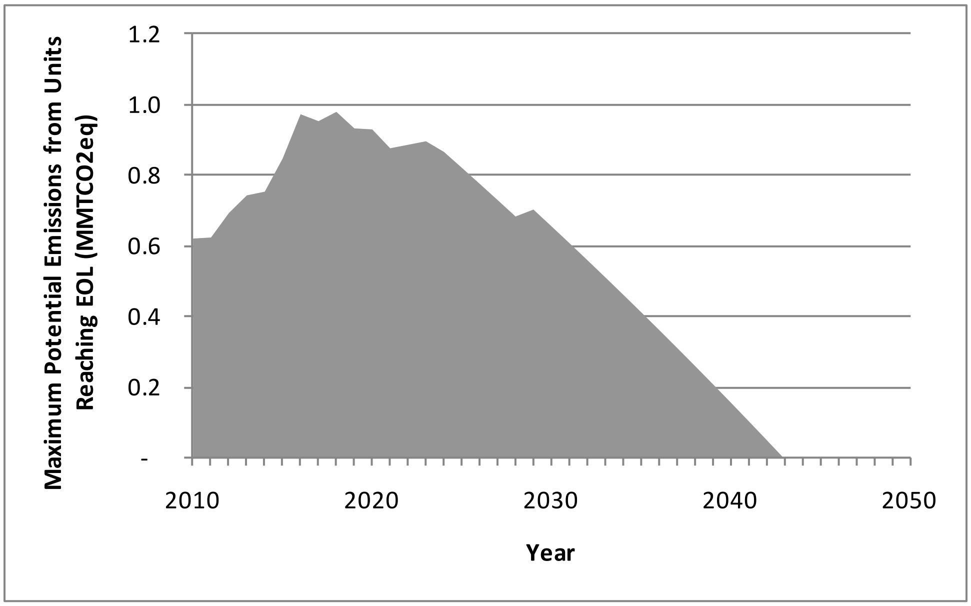
[a] Market penetration assumptions were developed by ICF in close consultation with Caleb Management Services Ltd (2010) and AHAM (2010), and are consistent with ARC (2010).

This analysis does not quantify the costs or benefits associated with the disposal of units containing HC or other low-GWP alternative foam blowing agents. Table I-6 presents the assumed number of retiring units containing ODS/HFC blowing agents, by blowing agent type from 2010 through 2050. As shown, all units containing ODS blowing agents are assumed to fully reach retirement by 2028, whereas all units containing HFC blowing agents are assumed to fully reach retirement by 2043. Figure I-6 graphically presents the associated climate impacts of blowing agents contained in refrigerators/freezers reaching EOL from 2010 through 2050. As shown, the peak year for reducing GHG emissions associated with the disposal of refrigerators/freezers is projected to be 2018.

Table I-6: Number of ODS/HFC Units Disposed in CA by Blowing Agent

Disposal Year	Number of ODS/HFC Units Disposed in CA by BA type				
	CFC 11	HFC 134	HCFC 141	HFC 245	Total ODS/HFC units
2010	—	19,596	960,188	—	979,784
2015	—	83,866	898,560	215,654	1,198,080
2020	—	—	419,497	711,770	1,131,267
2025	—	—	210,341	736,193	946,534
2030	—	—	—	700,870	700,870
2035	—	—	—	442,196	442,196
2040	—	—	—	170,011	170,011
2042	—	—	—	57,238	57,238
2043	—	—	—	—	—
2045	—	—	—	—	—
2050	—	—	—	—	—

Figure I-6: Potential Climate Impacts of Blowing Agent Reaching EOL (MMTCO$_2$eq), 2010-2050



Transport

Table I-7 presents the assumed distances traveled in each leg of transport. Average distances were roughly estimated based on the relative number and location of entities performing the relevant services.

Table I-7: Assumed Distances Between Entities in the Appliance Disposal Pathway

Step in Pathway (roundtrip)		One way Distance (miles)			
		BAU : CARs handle 85% of appliances, DARs handle 15%	Scenario 1: CARs perform foam removal	Scenario 2: all appliances sent to 10 DARs	Scenario 3: all appliances sent to 8 DARs with automated foam removal
A	End-user to CAR[a]	40	40	NA	NA
B	CAR to landfill (foam)	20	NA	NA	NA
C	CAR to WTE/MSW incineration facility (foam)	NA	20	NA	NA
D	End-user to DAR[a]	100	100	100	100
E	DAR to WTE/MSW incineration facility (foam)	20	20	20	NA
F	DAR (with automated foam removal) to destruction facility using approved technology (foam-blowing agent)	NA	NA	NA	750[c]
G	DAR (with automated foam removal) to landfill (foam fluff)	NA	NA	NA	20
Total per refrigerator, including roundtrips[b] (% of units)		120 (85%); 240 (15%)	120 (85%); 240 (15%)	240 (100%)	1,740 (100%)

[a] Distance from end-user to CAR and DAR reflect an averaged distance required to pick up a full load of refrigerators before returning to the CAR/DAR.
[b] Totals listed per refrigerator consider roundtrip distances that trucks must travel for the complete disposal of one refrigerator. They do not reflect fleet travel distances, since the number of trucks needed for different legs of transport depends on cargo load.
[c] The nearest known facility that accepts concentrated ODS/HFCs for destruction is in Aragonite, Utah.

It is assumed that trucks travel at an average speed of 50 mph for the longer trips (i.e., from a DAR to a hazardous waste permitted destruction facility), and 30 mph for the shorter trips, to account for non-highway driving and the frequent stops required during refrigerator pickup.[24]

In this analysis, all transport from end-users to CARs or dedicated recycling facilities and then to recyclers, incinerators, destruction/reclamation facilities, and landfills is assumed to occur in 28-foot trucks with the capacity to transport 35 refrigerators per truckload.[25] These trucks are assumed to transport up to 140 refrigerators-worth of foam, or 5,000 refrigerators-worth of

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[24] Estimated truck speeds are roughly based on a Canadian government study “Satellite-Based Provincial Truck Travel Speed Analysis,” available at: http://www.th.gov.bc.ca/Publications/planning/Provincial%20Highways/Truck_Travel_Time_Study.pdf.

[25] In reality, at least two sizes of trucks are used to transport refrigerators and recovered appliance components. To transport foam from the recovery site to destruction facilities, a standard 53-foot semi-trailer truck is used in Northern California, which can hold the volume a foam recovered from approximately 300 to 350 refrigerators, equivalent to roughly 3,000 to 3,500 pounds of insulation foam, while a 28-foot truck is used in Southern California, which can hold the volume of foam recovered from approximately 140 refrigerators (JACO 2009, ARCA 2009).

recovered blowing agent. For modeling simplification it is assumed that the trucks contain a full cargo load for 50% of transport and an empty load for the remaining 50%.

Energy Consumption

Energy consumption during dismantling and shredding equipment use is included in emissions calculations. An autoshredder is estimated to consume approximately 3 kWh/appliance, based on the U.S. EPA Durable Goods Calculator (EPA 2010b) and communication with CARs (SIMS 2010). To isolate the foam from the rest of the autoshredded materials, it is assumed that the energy associated with foam shredding is approximately 2% of the total (ARC 2010). Therefore, total per-unit energy consumption associated with foam shredding is approximately 0.06 kWh.

If appliance foam is removed manually rather than being shredded in an autoshredder, energy consumption is dependent on the removal equipment. Energy consumption associated with handheld saws is assumed to be negligible. However, it is assumed that half of the appliances handled by DARs in the BAU and in Scenarios 1 and 2 are handled with automated saws, which consume approximately 5 kWh/appliance (TEAP 2009).

Finally, fully automated appliance dismantling machines are assumed to consume approximately 35 kWh/appliance (TEAP 2009). Energy consumption for foam separation and foam blowing agent removal is estimated at 17.5 kWh/appliance, based on the assumption that the energy associated with foam separation is approximately 50% of the total.

Table I-8 summarizes the per-unit energy consumption assumptions associated with each appliance dismantling practice. Per-unit energy consumption is lowest in Scenario 1 and highest in Scenario 3.

Table I-8: Energy Consumption per Unit (kWh) Required to Operate Appliance Demanufacturing/ Disposal Machinery

Action	Energy Consumption per Unit Required to Recover Foam/ Blowing Agent (kWh)	Energy Consumption per Unit, Based on Scenario Pathways			
		BAU	Scenario 1	Scenario 2	Scenario 3
Blowing agent recovery in fully automated plant[a]	17.5	NA	NA	NA	100%
Foam shredding in auto shredder[b]	0.06	85%	NA	NA	NA
Manual foam removal using handheld saw	0.0	7.5%	92.5%	50%	NA
Manual foam removal using automated saw[c]	5.0	7.5%	7.5%	50%	NA
Total	NA	0.43	0.38	2.5	17.5

NA =Not applicable.

[a] Based on TEAP (2009), assuming that the energy consumption associated with foam separation (versus metal shredding/separation) is 50% of total per-unit energy consumption.

[b] Based on the U.S. EPA's Durable Goods Calculator and communications with SIMS Metal (2010), assuming that foam shredding accounts for 2% of total per-unit energy consumption for appliances in auto shredders.

[c] Based on TEAP (2009).

I.5.2. Estimating Emissions

Direct Emissions from Foam Loss

ODP and GWP Values of Foam Blowing Agents

ODP and GWP values vary by blowing agent. For consistency with California's GHG emissions and reductions goals set by AB 32, this analysis uses GWP values from the Intergovernmental Panel on Climate Change (IPCC) 1995 Second Assessment Report (SAR) where possible. For those GWP values not reported in the SAR (e.g., HCFC-141b, HFC-245fa), this analysis uses GWP values from the IPCC 2001 Third Assessment Report (TAR).

Had the analysis used more recently calculated GWP values from the IPCC 2007 Fourth Assessment Report (AR4), GWP emissions in each scenario would have been higher because the AR4's revised GWP values for foam-blowing agents are generally higher than in the SAR and TAR. Therefore, the emissions and potential reductions in this research report have been conservatively under-estimated. Table I-9 presents each foam-blowing agent's GWP values from the SAR, TAR, and AR4. The far right column indicates the increase or decrease in GWP values between 1995 and 2007.

Table I-9: Blowing Agent ODP and GWP from IPCC SAR, TAR, and AR4

Blowing Agent	Ozone Depleting Potential (ODP)[a]	GWP SAR (1995)	GWP TAR (2001)	GWP AR4 (2007)	Percent Change in GWP from SAR to AR4
CFC-11	1.0	3800	4600	4750	25%
HCFC-141b	0.12	N/A	700	725	4%
HFC-134a	0	1300	1300	1430	10%
HFC-245fa	0	N/A	950	1030	8%
Hydrocarbons (HCs)	0	N/A	N/A	<25[b]	—

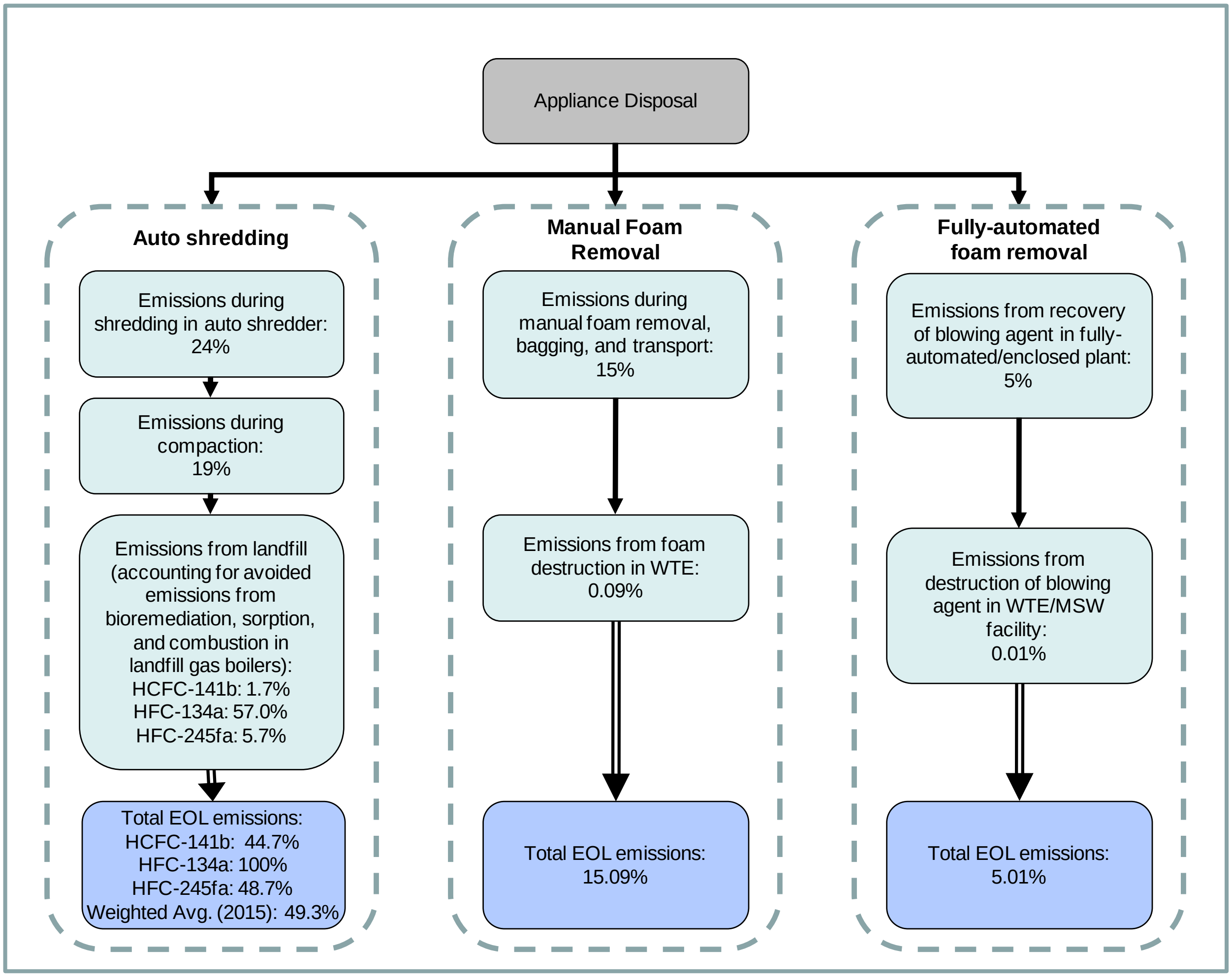
[a] ODP values are from the WMO (2007).

[b] Hydrocarbons are estimated to have a GWP of less than 25, according to TEAP (2009). However, for the purposes of this assessment, non-ODS, non-HFC blowing agents are assumed to have a GWP of zero, as they are a functionally negligible GHG source compared to high-GWP foam expansion agents, with less than 3% of the GWP of HCFC-141b.

Emissions from Foam at EOL

At EOL, emissions depend on the foam removal techniques. Figure I-7 presents the emissions profile for the three options for foam disposal at EOL: (1) shredding and landfilling; (2) manual removal and incineration; and (3) blowing agent removal in a fully-automated appliance dismantling machine and subsequent destruction.

Figure I-7: Foam Blowing Agent Emission Profiles From Appliance Disposal Options



When an appliance is sent through an autoshredder, it is assumed that approximately 24% of the blowing agent remaining at EOL is immediately released (Scheutz et al. 2007), with an additional 19% lost during compaction in a landfill (Fredenslund, et al. 2005, as reported in CAR 2010). Therefore, by the time the foam enters the landfill, only 57% of the blowing agent at EOL remains.[26] Actual losses may be greater, especially if shredded foam is used as a daily landfill cover, which is common practice in California.[27]

Once in a landfill, blowing agent is assumed to be either bioremediated, sorbed, combusted, or released. In reality, this release would occur gradually over many years. However, for modeling simplicity, this analysis assumes that all blowing agent reaches its ultimate fate in year 1. The amount of blowing agent lost during shredding (in an auto shredder), compaction, and over time

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[26] UNEP (2005) estimated emissions from foam shredding/landfilling at 8-40% of blowing agent remaining at EOL; Scheutz, C. et al. (2007) found a 24% average loss during blowing agent shredding; and the Climate Action Reserve Protocol (2010) estimates that post-shredding losses from compaction are approximately 19%, based on Fredenslund et al. (2005). It should be underscored, however, that the compaction estimate in Fredenslund et al. (2005) is based on modeling and is only an expert judgment, as no field studies have been performed to determine the losses of blowing agent in actual landfills (Kjeldsen 2010).

[27] Fredenslund et al. (2005) did not consider the impact of using insulation foam waste contained in autofluff as daily landfill—a practice that can lead to significantly higher initial compaction losses (Kjeldsen 2010).

(once in the landfill) varies by chemical type, since some bioremediation (e.g., anaerobic degradation), sorption, and/or combustion of landfill gases may effectively prevent emissions of certain blowing agents. Indeed, 23% of HCFC-141b is sorbed; it is assumed that this quantity is ultimately bioremediated and therefore not emitted (Scheutz et al. 2007b).[28] The remaining blowing agent is either bioremediated or released with landfill gases to be collected and combusted or emitted. Scheutz et al. (2007b)[29] have shown that under laboratory-simulated, *ideal* landfill conditions (i.e., uniform mixing of moderately sized chunks of foam with anaerobic sludge and no compaction), there is the potential for bioremediation of up to 94% of the blowing agent (i.e., CFC-11) that reaches a landfill; this translates to 0-54% bioremediation of the blowing agent available at EOL, depending on the type of blowing agent; no HFC blowing agent was found to be bioremediated (Scheutz et al. 2007b). In this analysis, only HCFC-141b is assumed to be bioremediated, at a rate of 48% of the blowing agent entering the landfill, or 27% of the quantity available at end of life;[30] given that this estimate is based on laboratory-simulated, ideal landfill conditions, actual bioremediation rates for HCFC-141b will be lower under real-world landfill conditions

Blowing agent that is not bioremediated can be combusted in landfill gas chambers. Combustion of available HCFC-141b and HFC-245fa is estimated at 90%, whereas HFC-134a is not expected to combust at typical landfill gas flare temperatures (Caleb Management Services Ltd 2009; Dellinger et al. 2010).[31] Therefore, 26.1% of the HCFC-141b (or 90% of the 29% that is not bioremediated or sorbed) and 90% of the HFC-245fa entering the landfill is combusted (as no HFC-245fa is bioremediated or sorbed). Over time, the remaining blowing agent is emitted from the landfill (approximately 2.9% of landfilled HCFC-141b, 10% of landfilled HFC-245fa, and 100% of landfilled HFC-134a). Ultimately, between 1.65% and 57% of blowing agent at EOL is emitted from the landfill, and total EOL emissions range from 44% to 100%, depending on blowing agent type. In 2015, the weighted average EOL emissions (based on the make-up of blowing agent types reaching the landfill) is approximately 49%.

According to UNEP (2002), when foam is destroyed in municipal solid waste (MSW) incinerators rather than landfilled, approximately 0.09% of blowing agent is released, based on the minimum DRE achieved in studies. This analysis assumes the same release rates for foam destruction in WTE boilers.

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[28] This analysis assumes no sorption of HFC blowing agents. However, because HFCs have not been shown to degrade in landfills (Scheutz et al. 2003, 2007b), any sorption would only delay, not reduce, emissions of these blowing agents.

[29] Scheutz et al. (2007b) examined various samples of foam mixed with organic waste collected from (a) private Danish households, (b) an American landfill situated in North Carolina, and (c) a laboratory experimental digester containing refuse. Analyses were performed under laboratory conditions in glass bottles.

[30] The Climate Action Reserve's U.S. ODS destruction carbon offset project protocol assumes that lifetime emission rates of appliances at EOL is 50% for HCFC-141b. HFC blowing agents are not covered under the Protocol.

[31] Estimates of combustion in landfills are based on (1) studies of CFC and HCFC combustion efficiency conducted by Environment Canada, as reviewed in Caleb (2009); (2) a comparison of the properties of HFC-245fa with HCFC-141b and halon 1301, which are expected to behave similarly in landfill flares due to similar auto-destruction temperatures and structures; and (3) a comparison of the properties of HFC-134a vs. HCFC-123. The combustion of halon 1301 and HCFC-123 was studied in detail by Dellinger et al. (2010), the results of which support the assumption that 90% of HCFC-141b and HFC-245fa will be combusted in landfill flares, whereas essentially zero HFC-134a will be combusted to any significant destruction efficiency given typical landfill gas flare temperatures and residence times. Further study into the combustibility of these chemicals is needed to develop definitive conclusions regarding their actual combustibility in U.S. landfills.

It is assumed that approximately 15% of the blowing agent remaining at time of disposal is emitted during manual foam recovery.[32] For automated foam recovery, blowing agent losses are estimated at only 5% (UNEP 2005). Once the blowing agent is extracted from the foam fluff, it is sent to a reclamation/destruction facility where it is destroyed with 99.99% efficiency.[33]

Table I-10 presents the total losses by blowing agent on a per-unit basis. Losses are based on the quantity remaining at EOL shown previously in Table I-3. As shown, significant CO_2 emissions savings result from manual or fully automated foam removal practices, relative to shredding and landfilling the foam.

Table I-10: Per Unit Blowing Agent Losses and Emissions Avoided at EOL by Foam Handling Technique

Foam Handling Technique	Total Losses at EOL		Total Emissions Avoided, Relative to Autoshredding and Landfill		
	Percent (%)	Quantity (lbs.)	Percent (%)	Quantity (lbs.)	Quantity ($MTCO_2eq$)
Autoshredding foam	44.7–100	0.88–1.66	NA	NA	NA
Manual removal and incineration	15.09	0.25–0.33	29.6–84.9	0.58–1.41	0.19–0.83
Separation of blowing agent in fully automated plant and subsequent destruction	5.01	0.08–0.11	39.6–95.0	0.78–1.57	0.25–0.93

Sources: ICF 2009a; ICF 2009c; Jeffs 2010; Scheutz et al. 2007, 2007b; Fredenslund et al. 2005; Kjeldsen 2010; CAR Protocol 2010; Caleb 2009; UNEP 2005.

Indirect GHG and Criteria Pollutant Emissions from Recycling vs. Landfilling of Durable Components

This analysis assumes that all metals, plastics, and glass are currently being recycled in the BAU, and would be similarly treated in all regulatory Scenarios. Therefore, the handling of these materials is not included in the calculations and is considered outside the boundaries of the analysis.

GHG and Criteria Pollutant Emissions from Transport

Table I-11 presents the assumed fuel efficiency of trucks carrying each appliance component load, and the resulting emissions assumed per mile. Diesel fuel is assumed to have a lower heating value (LHV) of 135.5 MJ/gal and a CO_2eq emission factor of 94.7 g CO_2eq/MJ, based on GREET 1.8b used for the California Low Carbon Fuel Standard (ARB 2009b).[34]

Table I-11: Truck Fuel Efficiency and Emissions per Mile ($kgCO_2eq$/mile) with Varying Cargo Loads

Load	Appliances Per Truckload	Total Truckload Cargo Weight	Fuel Efficiency[a] (mpg)	Emissions per Mile ($kgCO_2eq$/mile)
Blowing agent	5,000	12,000	7.2	1.78
Whole appliances	35	6,573	8.3	1.55
Foam	140	2,982	9.4	1.37
Foam fluff	140	2,702	9.5	1.35
Empty truck	NA	0	10.3	1.25

[a] Fuel Efficiency is based on the U.S. EPA Physical Emissions Rate Estimator Model for Heavy-Duty Vehicles (PERE-HD) Calculator (EPA 2010).

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[32] This assumption is based on ICF conversations held with the Appliance Recycling Centers of America, Inc. (ARCA) and JACO Environmental, Inc. (JACO), whose estimates ranged from 5-25%, as well as UNEP (2005), which reports that emissions from manual foam removal can range from 10-15% but could be lower if best practices are used.

[33] Blowing agent recovered from foam is likely to be destroyed at a minimum DRE of 99.99% (e.g., if it is destroyed in a rotary kiln): if blowing agent is destroyed in a PCB (hazardous waste-permitted) rotary kiln incinerator, the DRE will be 99.9999%.

[34] The CO_2eq emission factor for diesel fuel includes well-to-tank (WTT) and tank-to-wheel energy and greenhouse gas values and vehicle fuel emissions for California Ultra Low-Sulfur Diesel (ULSD).

Criteria pollutant emissions associated with transport are based on the emission factors presented in Table I-12, based on Façanha and Horvath (2007). It should be noted that criteria air pollutant emission factors reflect global emission estimates; due to analytical limitations, emissions for criteria air pollutants could not be disaggregated for California specific regions or air districts.

Table I-12: Criteria Pollutant Transport Emission Factors (g/mile)[a]

Load	NO_x (g/mile)	PM10 (g/mile)	PM2.5 (g/mile)	SO_2 (g/mile)
Blowing agent	14.49	0.40	0.07	0.37
Whole appliances	8.62	0.24	0.04	0.22
Foam	3.60	0.10	0.02	0.09
Foam fluff	3.26	0.09	0.02	0.08
Empty truck	—	—	—	—

[a] Emission factors account for fuel combustion and pre-combustion.
Source: Façanha and Horvath (2007).

Indirect Emissions from Energy Consumption

Table I-13 presents the emission factors used to calculate indirect GHG and criteria pollutant emissions associated with the energy consumed during appliance dismantling.

Table I-13: Emission Factors Associated with Energy Consumption

	Energy Consumption Emission Factors (g/kWh)				
	g CO_2eq/kWh[a]	g NO_x/kWh	g PM10/kWh	g PM2.5/kWh	g SO_x/kWh
Energy Consumption	751.50	1.18	1.02	0.27	2.60

[a] The CO_2eq emission factor represents net CO_2, which includes CO_2, CO, and VOCs.
Source: GREET 1.8c

I.5.3. Estimating Costs

In this analysis, the following costs are quantified:

- Transport costs
- Labor costs
- Energy costs
- Operations and maintenance costs
- Foam disposal costs
- Capital costs of facility rental and equipment purchase.

The assumed number of units associated with the annual costs, by management scenario, is summarized in Table I-14. The detailed assumptions used to estimate both annual and capital costs are described further below.

Table I-14: Annual Costs Included in Analysis

Costs	Percent of EOL Units to Which Costs Apply			
	BAU	Scenario 1: CARs/DARs/Manual	Scenario 2: DARs/Manual	Scenario 3: DARs/Automated
Transport (fuel and labor)				
Refrigerators/freezers from end-user to CARs	85%	85%	0%	0%
Refrigerators/freezers from end-user to DARs	15%	15%	100%	100%
Foam to landfill	85%	0%	0%	0%
Bagged foam to WTE/MSW incinerator	15%	100%	100%	0%
Foam-blowing agent to hazardous waste permitted destruction facility in Utah	0%	0%	0%	100%
Foam fluff (void of blowing agent) to landfill	0%	0%	0%	100%
Labor				
Shredding foam (auto shredder)	85%	0%	0%	0%
Recovering foam, manual	15%	100%	100%	0%
Recovering foam blowing agent, automated	0%	0%	0%	100%
Energy Consumption				
Shredding foam (auto shredder)	85%	0%	0%	0%
Recovering foam, manual (with electric saw)	15%	100%	100%	0%
Recovering foam, automated	0%	0%	0%	100%
Foam Disposal				
Landfilling foam	85%	0%	0%	0%
Incinerating foam	15%	100%	100%	0%
Destroying foam blowing agent	0%	0%	0%	100%
Operations and Maintenance Costs				
Auto shredders	85%	85%	0%	0%
DARs	15%	15%	100%	100%

Transport Cost Assumptions

Transport fuel costs are based on an assumed diesel price of $2.54/gallon.[35] Transport labor is estimated based on an assumed average truck speed of 30 mph for shorter distances and 50 mph for the large distance traveled between DAR and blowing agent hazardous waste permitted destruction facility.[36]

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[35] Fuel prices are based on US estimates provided at: http://tonto.eia.doe.gov/oog/info/wohdp/diesel.asp. Price is accurate as of July 2009 (EIA 2009). Although fuel costs have increased to above $4.00/gallon as of June 2011, the increased fuel cost is estimated to increase total cost of each management scenario by only 1%; due to scope of work issues, re-calculating all transport costs was not feasible.

[36] Estimated truck speeds are roughly based on a Canadian government study “Satellite-Based Provincial Truck Travel Speed Analysis,” available at: http://www.th.gov.bc.ca/Publications/planning/Provincial%20Highways/Truck_Travel_Time_Study.pdf. (Canadian Government. Undated)

Labor Cost Assumptions

All labor costs are based on an assumed labor rate of $40/hr for technicians and truck drivers (ARB 2009). Table I-15 presents the assumed person-hours and associated costs required to handle appliances.

Table I-15: Person-Hours Required to Operate Appliance Disposal Machinery[a]

Action	Person Hours per Unit	Labor Cost per Unit
Fully Automated Plant[b]: Foam-Blowing Agent Recovery	0.12	$9.00
Auto Shredder[c]: Foam Shredding	0.002	$0.15
Handheld Saws: Manual Foam Removal	0.4	$30.00
Automated Saws: Manual Foam Removal	0.4	$30.00

[a] These estimates are based on assumptions that 25 units can be processed per hour by a fully automated/fully enclosed plant operated by 6 technicians; 20 units can be processed per hour by an auto-shredder operated by 2 technicians; and 2.5 units can be processed per hour using a handheld or automated saw to break the appliance and manual foam removal techniques by 1 technician. These assumptions are based on conversations with ARCA and JACO (ARCA 2009, 2010; JACO 2009, 2010).

[b] Person-hours required for recovery of foam-blowing agent are estimated by scaling down the total person-hours needed to process a whole appliance; it is assumed that the time associated with foam blowing agent separation is approximately 50% of the total, for consistency with the energy assumptions (ARC 2010).

[c] Person-hours required for foam shredding are estimated by scaling down the total person-hours needed to process a whole appliance; it is assumed that the time associated with foam shredding is approximately 2% of the total, for consistency with the energy assumptions (ARC 2010)

Recycling Costs Savings

Due to the market value of recycled materials, recycling of metals, plastics, and glass in lieu of manufacturing virgin materials results in savings. Recycled metals are worth approximately $100/ton (SA Recycling 2009a, SA Recycling 2010), while plastics and glass are not nearly as valuable. The handling of metals, plastics, and glass is considered beyond the scope of this analysis, given that these materials are assumed to be recycled under each scenario.

Energy Costs

Costs associated with energy consumption during appliance dismantling are based on an estimated cost of $0.11/kWh (EIA 2010). This energy cost is not assumed to change over time, which is likely to underestimate future costs. Based on the assumed per-unit energy consumption presented in Table I-8, Table I-16 summarizes total per-unit energy consumption costs in each scenario.

Table I-16: Energy Consumption Costs per Unit ($) Required to Operate Appliance Disposal Machinery

Action	Cost per Unit	Energy Cost per Unit, based on Scenario Pathways			
		BAU	Scenario 1	Scenario 2	Scenario 3
Fully Automated Plant: Foam-blowing agent recovery	$ 1.93	—	—	—	100%
Auto Shredder: Foam shredding	$ 0.01	85%	—	—	—
Handheld Saws: Manual Foam removal	$ 0.00	7.5%	92.5%	50%	—
Automated Saws: Manual Foam Removal	$ 0.55	7.5%	7.5%	50%	—
Total	NA	$ 0.05	$ 0.04	$ 0.28	$ 1.93

Capital Costs

In all management scenarios, new equipment is necessary. In Scenario 1, it is assumed that the 130 CARs purchase basic equipment for the manual recovery of foam. This includes a hand-held electric reciprocating saw, known as a “Saws-all,” which is readily available at any home appliance store for approximately $100-$150. In addition, a tool such as an ice scraper must be used to separate the foam from the metal and plastic, and can be purchased for approximately $30. Therefore, total equipment costs for manual foam removal with handheld saws range from approximately $130-$180 (JACO 2009). It is assumed that each saw costs approximately $150 and has a lifetime of 500 units, and each saw blade costs $0.75 with a lifetime of 10 units. Therefore, total equipment costs for manual foam removal are approximately $0.40/unit.

Larger types of equipment, such as the Wellsaw large band automated saws used in dedicated appliance recycling facilities, cost approximately $50,000-$65,000 (JACO 2009). This equipment is assumed to have a lifetime of 10 years. Scrapers and cable cutters are also used in this process. These capital costs are assumed to be incurred in 2010, 2020, and 2030; capital costs are not assumed to be incurred in 2040, due to the significantly lower throughput of units containing HFC blowing agents assumed to be reaching EOL (as an increasingly large percent of disposed units will contain low-GWP blowing agents [see Table I-6]). These automated saws are assumed to be used by half of the DARs in the BAU, and in Scenario 2, it is assumed that three of the seven new facilities use them. It is also assumed that the three facilities each purchase approximately 20 automated saws[37], for a total of $3.4 million, and that the other four facilities use handheld saws at a cost of $0.40/unit.

Fully automated plants, which are purchased by the five new facilities as well as the three existing facilities in Scenario 3, each cost approximately $5 million (JACO 2009, ARCA 2009). This equipment has an approximate lifetime of 10 years. These capital costs are assumed to be incurred in 2010, 2020, and 2030, but not in 2040. This is because a lower throughput of units containing high-GWP blowing agents is assumed to be processed beyond 2030, as an increasingly large percent of disposed units will contain low-GWP blowing agents (see Table I-6).

Finally, in Scenarios 2 and 3, new 70,000 sq. ft. facilities must be used. It is assumed that the cost to lease this size of warehouse facilities in California is approximately $500,000, based on an approximate annual cost of $7/sq ft. (JACO 2010b, LoopNet 2010). These costs do not include any permitting fees that may be incurred. Annual rental costs are included through 2042, after which point it is assumed that all units containing ODS/HFC blowing agents will have reached full retirement.

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[37] It is assumed that each unit requires 0.4 person-hours for processing. Annual throughput at manual facilities is assumed to be approximately 150,000 units. If the facility operates all year for 8 hours/day, 20 automated saws would be needed per facility to handle the annual load.

O&M Costs and Utility Subsidies at DARs

In addition to the capital costs of facility rental and equipment purchase, CARs and DARs incur operations and maintenance (O&M) costs. It is estimated that O&M costs at auto shredders are approximately $0.11 per refrigerator/freezer, primarily for maintenance and repair costs (including safety supplies, operating supplies, oils and lubricants, wear parts, and equipment parts) (SA Recycling 2011).

At DARs, O&M costs are assumed to be covered by the per-unit fees currently paid by utilities. In the BAU, utilities conducting Demand-side Management (DSM) programs currently pay DARs approximately $20/unit to cover the added costs of operations to recover and manage appliance foam. This "subsidy" is in addition to direct costs associated with appliance processing or other DSM-related program costs such as incentives and marketing. This assessment assumes a $20/unit subsidy for all units handled by DARs, which covers the O&M costs as well as an undisclosed amount of profit; however, the actual value of the subsidy may vary widely depending on the size of the operation, location, etc. It should also be noted that the electric utilities subsidize appliance recycling primarily to remove older, inefficient appliances from the electric grid, and not as a greenhouse gas reduction strategy.

Offsetting Higher O&M Costs for CARs and DARs

The O&M costs for CARs and DARs are higher when foam recovery/destruction is performed. These higher costs can be covered by a variety of sources—including utility subsidies (as are currently provided in U.S. DSM programs), municipal taxes (as in the United Kingdom), consumer disposal fees (as in Japan), levies on the sale of new refrigerators/freezers, or other sources (see Appendix A: Lessons Learned on Appliance Recycling from Other Countries for lessons learned on appliance recycling in Japan and the UK). This would represent a shift in appliance recycling from a commodity to a service model with potentially negative unintended consequences.

Foam Disposal Costs

Based on discussions with recycling companies, landfill tipping fees are estimated to be approximately $65/tonne.[38] These fees are assumed to apply to the shredded foam landfilled in the BAU and the foam fluff landfilled in management Scenario 3.

Foam that is recovered from appliances during manual foam removal is bagged and sent to a destruction facility for incineration. Incineration charges are estimated to be approximately $500/tonne (JACO 2010b). Therefore, the fee per refrigerator/freezer is approximately $5 (based on an average 21 lbs. of foam per unit).

When recovered (concentrated) foam blowing agent is sent to a hazardous waste-permitted destruction facility, incineration charges are assumed to be $2.50/lb.[39] Therefore, the fee per refrigerator/freezer is approximately $3.93-$5.16 in Scenario 3, depending on the amount of blowing agent by type available at EOL. HC blowing agents are not assumed to be destroyed in a hazardous waste combustor (HWC).

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[38] Direct communication with Republic Waste Services indicated average tipping fees of $50-100/ton (August 4, 2010). Anecdotal evidence suggests average may be closer to the low end of this range.

[39] Based on confidential business information provided by U.S. companies for this report, ICF estimates that the price charged to customers for refrigerant destruction varies depending on a variety of factors, including gas type, volume, and whether or not the customer is long-term or short-term. Long-term customers sending large quantities of refrigerants on a regular basis will generally be charged less—between $0.50 and $2.00 per pound.

Blowing agent destruction costs may be balanced by the opportunity to receive carbon credits from the destruction of ODS foam blowing agent. ODS destruction projects are now eligible for carbon credits under a number of standards in the voluntary carbon market, including the Climate Action Reserve (the Reserve). The Reserve protocol allows both ODS refrigerant and concentrated ODS foam blowing agent from appliances originating in the United States to be destroyed at certified U.S. facilities in exchange for carbon credits. The revenue that can be generated from carbon credits varies based on a number of factors, including carbon price. In 2010, the price of carbon offset credits on the Reserve generally ranged from $5 to $10 per metric ton of carbon dioxide equivalent (MTCO$_2$e). Assuming roughly 2 lbs. of HCFC-141b blowing agent are recovered per unit, foam recovery and destruction can result in an approximate carbon offset credit of roughly $3.15/unit, assuming a price of $10/MTCO$_2$eq.[40]

I.6. Cost Assessment

This section estimates the capital and annual costs associated with appliance disposal in the baseline and in the management scenarios. Costs are associated with recycling, landfilling, destruction, and reclamation of appliance components. In the baseline, total costs are estimated, with only incremental costs estimated for the alternative scenarios. Costs are also shown on a per-unit basis.

I.6.1. BAU Costs

Costs in the BAU are calculated based on estimated labor time for appliance dismantling, diesel fuel prices, foam disposal fees, operations and maintenance costs, and an assumed labor rate of $40/hour. Annual costs will increase as the number of appliances being disposed increases over time. Table I-17 presents annual costs in the BAU in 2010.

Table I-17: Total Annual Costs in the BAU in 2010

Costs Source	Summary Assumptions	Annual Costs	Average Cost per Appliance
Transport: Fuel Consumption	Cost of diesel fuel ($2.54/gallon) at fuel efficiencies shown in Table I-11 and distances shown in Table I-7.	$821,459	$0.84
Labor: Transport	Labor time required to transport appliances and/or appliance components (speed of 30 mph, distance of 120–240 miles).	$4,031,111	$4.11
Labor: Foam Handling	Labor time (0.05 person-hours per unit) required to send appliances through auto shredder (scaled down to reflect the foam volume percentage of the whole appliance) or to use manual foam removal techniques (0.4 person-hours per unit)—foam is landfilled, no foam blowing agent recovery.	$2,418,107	$2.47
Energy Consumption: Foam Handling	Auto shredder (0.06 kWh/appliance) and automated saw (5 kWh/appliance); at $0.11/kWh.	$45,913	$0.05
Foam Disposal Fees	Foam landfilling fees ($65/ton); Foam incineration fees ($500/ton)	$1,232,966	$1.26
O&M Costs	$0.11/unit at auto shredders; $20/unit at DARs	$3,030,962	$3.09
Capital Costs: Facility Rental and Equipment Purchase	No capital costs assumed	$0	$0.00
Total		$11,580,517	$11.82

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[40] This value assumes a 50% CO$_2$e discounting for BAU emissions avoided in landfill but does not include discounting associated with transport and destruction, nor does it account for project costs (e.g., registration, administration, verification, measurements, reporting, etc.) which would lower total value.

As shown, the total annual cost associated with appliance disposal in California in 2010 is estimated at approximately $11.6 million per year, or roughly $12/unit.

I.6.2. Scenario 1 Incremental Costs: All CARs and DARs Using Manual Foam Removal

In Scenario 1, incremental annual costs of foam removal labor are incurred, as well as increased foam disposal fees for incineration. These incremental costs are partially offset by reduced energy consumption associated with handling foam in lieu of auto shredding it. Transport fuel and labor costs are the same as in the BAU. In addition, capital costs of purchasing manual saws ($0.40/unit) are incurred in Scenario 1. As shown in Table I-18, total incremental costs associated with Scenario 1 in 2010 are nearly $17.1 million relative to the baseline, or approximately $17.44 more per unit.

Table I-18: Total Incremental Costs in 2010 for Scenario 1 Relative to BAU

Costs Source	Summary Assumptions	Incremental Annual Costs	Average Cost per Appliance
Transport: Fuel Consumption	Cost of diesel fuel ($2.54/gallon) at fuel efficiencies shown in Table I-11 and distances shown in Table I-7	—	—
Labor: Transport	Labor time required to transport appliances and/or appliance components (speed of 30 mph, distance of 120-240 miles)	—	—
Labor: Foam Handling	Labor time required to use manual foam removal techniques (0.4 person-hours per unit)	$13,258,437	$13.53
Energy Consumption: Foam Handling	Automated saw (5 kWh/appliance); at $0.11/kWh	$(5,497)	$(0.01)
Foam Disposal Fees	Foam incineration fees ($500/ton)	$3,500,109	$3.57
O&M Costs	$0.11/unit at auto shredders; $20/unit at DARs	$0	—
Capital Costs: Facility Rental and Equipment Purchase	Handheld saws ($0.40/unit)	$333,127	$0.34
Total		$17,086,176	$17.44

Table I-19 presents incremental costs from 2010 through 2050. Net present value (NPV) costs are calculated based on a discounting rate of 5%. As shown, incremental annual costs in this scenario are associated with facility and equipment costs and foam removal and destruction (since foam would be removed from 100% of units instead of 15% as in the BAU). These costs are partially offset by reduced energy consumption (associated with the lack of foam shredding).

Table I-19: Incremental Costs ($) for Scenario 1 (2010-2050)

Year	Transport Costs	Labor: Transport	Labor: Foam Handling	Energy Consumption	Foam Disposal Fees	O&M Costs	Facility and Equipment Costs	Total Incremental Costs
2010	$0	$0	$13,258,437	($5,497)	$3,500,109	$0	$333,127	$17,086,176
2015	$0	$0	$16,212,419	($6,721)	$4,279,934	$0	$407,347	$20,892,979
2020	$0	$0	$15,308,298	($6,346)	$4,041,254	$0	$384,631	$19,727,837
2025	$0	$0	$12,808,505	($5,310)	$3,381,331	$0	$321,822	$16,506,347
2030	$0	$0	$9,484,176	($3,932)	$2,503,738	$0	$238,296	$12,222,277
2035	$0	$0	$5,983,793	($2,481)	$1,579,668	$0	$150,347	$7,711,326
2040	$0	$0	$2,300,584	($954)	$607,334	$0	$57,804	$2,964,768
2045	$0	$0	$0	$0	$0	$0	$0	$0
2050	$0	$0	$0	$0	$0	$0	$0	$0
2010–2050	$0	$0	$349,976,082	($145,091)	$92,390,567	$0	$8,793,369	$451,014,928
2010–2050 NPV	$0	$0	$209,702,887	($86,937)	$55,359,694	$0	$5,268,917	$270,244,560

I.6.3. Scenario 2 Incremental Costs: New and Existing DARs Using Manual Foam Removal

In Scenario 2, incremental costs of facility operations and maintenance, transport fuel and labor, foam removal labor, and foam disposal fees are incurred. These incremental costs are partially offset by the reduced energy and labor costs associated with foam shredding in an auto shredder. In addition, facility rental and equipment purchase costs are incurred due to the purchase of handheld and automated saws and the rental of 7 additional facilities through 2042. As shown in Table I-18, total annual incremental costs associated with Scenario 2 in 2010 are $42.1 million relative to the baseline, or an additional $43 per unit.

Table I-20: Total Incremental Costs in 2010 for Scenario 2 Relative to BAU

Costs Source	Summary Assumptions	Incremental Costs	Average Cost per Appliance
Transport: Fuel Consumption	Cost of diesel fuel ($2.54/gallon) at fuel efficiencies shown in Table I-11 and distances shown in Table I-7	$779,128	$0.80
Labor: Transport	Labor time required to transport appliances and/or appliance components (speed of 30 mph, distance of 240 miles)	$3,807,161	$3.89
Labor: Foam Handling	Labor time required to use manual foam removal techniques (0.4 person-hours per unit)	$13,258,437	$13.53
Energy Consumption: Foam Handling	Automated saw (5 kWh/appliance); at $0.11/kWh	$223,528	$0.23
Foam Disposal Fees	Foam incineration fees ($500/ton)	$3,500,109	$3.57
O&M Costs	$20/unit at DARs	$16,564,718	$16.91
Capital Costs: Facility Rental and Equipment Purchase	$3.5 million annual facility rental for 7 facilities; automated saws ($57,000 per equipment with 10-year lifetime) and handheld saws ($0.40/appliance)	$4,011,057[a]	$4.09[a]
Total		$42,144,138	$43.01

[a] Costs for equipment with a 10 year lifetime are annualized to more accurately represent the per-unit total costs in 2010.

Table I-21 presents incremental costs from 2010 through 2050. Net present value (NPV) costs are calculated based on a discounting rate of 5%. As shown, incremental annual cost in this scenario are associated with: labor costs for foam removal, since foam would be removed from 100% of units instead of 15% as in the BAU; transport labor and fuel costs, due to the increased distances units must travel from end-users to DARs rather than to CARs; and energy consumption, due to increased use of automated saws for foam removal.

Table I-21: Incremental Costs ($) for Scenario 2 (2010-2050)

Year	Transport Costs	Labor: Transport	Labor: Foam Handling	Energy Consumption	Foam Disposal Fees	O&M Costs	Facility and Equipment Costs[a]	Total Incremental Costs
2010	$779,128	$3,807,161	$13,258,437	$223,528	$3,500,109	$16,564,718	$7,656,563	$45,789,645
2015	$952,718	$4,655,397	$16,212,419	$273,330	$4,279,934	$20,255,340	$3,703,674	$50,332,811
2020	$899,588	$4,395,778	$15,308,298	$258,087	$4,041,254	$19,125,757	$7,682,315	$51,711,078
2025	$752,688	$3,677,963	$12,808,505	$215,942	$3,381,331	$16,002,585	$3,660,911	$40,499,925
2030	$557,335	$2,723,381	$9,484,176	$159,897	$2,503,738	$11,849,262	$7,609,148	$34,886,936
2035	$351,636	$1,718,246	$5,983,793	$100,883	$1,579,668	$7,475,982	$3,575,173	$20,785,380
2040	$135,193	$660,613	$2,300,584	$38,786	$607,334	$2,874,285	$3,528,902	$10,145,697
2045	$0	$0	$0	$0	$0	$0	$0	$0
2050	$0	$0	$0	$0	$0	$0	$0	$0
2010–2050	$20,566,248	$100,495,645	$349,976,082	$5,900,351	$92,390,567	$437,250,269	$131,866,684	$1,138,445,846
2010–2050 NPV	$12,323,132	$60,216,192	$209,702,887	$3,535,443	$55,359,694	$261,996,886	$69,387,130	$672,521,363

[a] Facility and equipment costs shown here are not annualized (as they are in Table I-21).

I.6.4. Scenario 3 Incremental Annual Costs: New and Existing DARs Using Fully Automated Machine

In Scenario 3, incremental costs of transport labor and fuel consumption, foam handling labor and energy consumption, operations and maintenance, and foam blowing agent destruction fees are incurred under this scenario. Incremental capital costs are assumed to be $40 million for the purchase of eight fully automated appliance dismantling machines for the existing and new DAR facilities ($5 million/unit); this equipment is assumed to be replaced every 10 years through 2030. In addition, five facilities will be leased each year through 2042, at an annual cost of $2.5 million. As shown in Table I-22, total incremental costs associated with Scenario 3 in 2010 are nearly $36.0 million relative to the baseline, or roughly $36.73 more per unit.

Table I-22: Total Incremental Costs in 2010 for Scenario 3 Relative to BAU

Costs Source	Summary Assumptions	Incremental Annual Costs	Average Cost per Appliance
Transport: Fuel Consumption	Cost of diesel fuel ($2.54/gallon) at fuel efficiencies shown in Table I-11 and distances shown in Table I-7	$864,814	$0.88
Labor: Transport	Labor time required to transport appliances and/or appliance components (speed of 30 mph, for long distances 50 mph, total distance approximately 1,730 miles)	$4,042,309	$4.13
Labor: Foam Handling	Labor time (0.12 person-hours per unit) required to send appliances through fully automated appliance dismantling machine (scaled down to reflect the foam volume percentage of the whole appliance)	$2,284,856	$2.33
Energy Consumption: Foam Handling	Fully automated appliance dismantler (17.5 kWh/appliance); at $0.11/kWh	$1,840,172	$1.88
Foam Disposal Fees	Blowing agent destruction ($2.50/lb) ; foam fluff landfill tipping fee ($65/ton)	$4,437,848	$4.53
O&M Costs	$20/unit at DARs	$16,564,718	$16.91
Capital Costs: Facility Rental and Equipment Purchase	Equipment purchase ($5 million per facility) at 8 facilities (annualized to account for 10-year lifetime); $2.5 million annual rental fee for 5 facilities	$5,953,567[a]	$6.08[a]
Total		$35,988,284	$36.73

[a] Costs for equipment with a 10 year lifetime are annualized to more accurately represent the per-unit total costs in 2010.

Table I-22 presents total incremental costs from 2010 through 2050. Net present value (NPV) costs are calculated based on a discounting rate of 5%. As shown, the total incremental cost in this Scenario 3 are associated with transport and material handling labor, as well as energy consumption during foam removal, due to the use of fully automated appliance dismantling machines.

Table I-23: Incremental Costs ($) for Scenario 3 (2010-2050)

Year	Transport Costs	Labor: Transport	Labor: Foam Handling	Energy Consumption	Foam Disposal Fees	O&M Costs	Facility and Equipment Costs[a]	Total Incremental Costs
2010	$864,814	$4,042,309	$2,284,856	$1,840,172	$4,437,848	$16,564,718	$42,500,000	$72,534,717
2015	$1,057,495	$4,942,936	$2,793,923	$2,250,162	$5,291,692	$20,255,340	$2,500,000	$39,091,547
2020	$998,522	$4,667,282	$2,638,113	$2,124,677	$5,095,392	$19,125,757	$42,500,000	$77,149,744
2025	$835,467	$3,905,131	$2,207,318	$1,777,724	$4,249,228	$16,002,585	$2,500,000	$31,477,454
2030	$618,629	$2,891,590	$1,634,429	$1,316,332	$3,130,763	$11,849,262	$42,500,000	$63,941,006
2035	$390,308	$1,824,373	$1,031,200	$830,505	$1,975,273	$7,475,982	$2,500,000	$16,027,642
2040	$150,061	$701,415	$396,465	$319,304	$759,432	$2,874,285	$2,500,000	$7,700,962
2045	$0	$0	$0	$0	$0	$0	$0	$0
2050	$0	$0	$0	$0	$0	$0	$0	$0
2010–2050	$22,828,059	$106,702,729	$60,312,166	$48,574,053	$115,949,291	$437,250,269	$202,500,000	$994,116,565
2010–2050 NPV	$13,678,392	$63,935,427	$36,138,570	$29,105,186	$69,500,441	$261,996,886	$121,638,801	$595,993,703

[a] Facility and equipment costs shown here are not annualized (as they are in Table I-22).

I.7. Benefits

Based on the pathways and boundaries established in Sections I.3 and I.4, this section presents the estimated lifecycle impacts on ODP, GHG, and criteria air pollutant emissions in the BAU and the three alternative management scenarios. More specifically, ODP emissions impacts are based on direct emissions of blowing agent at appliance disposal. In estimating GHG impacts, this assessment estimates the direct emissions associated with foam blowing agent losses, as well as the indirect emissions associated with transport and energy consumption. Criteria air pollutant emissions are quantified for transport and energy consumption.

I.7.1. BAU Emissions

ODP Emissions

Annual ODP emissions in the BAU are calculated based on direct foam emissions at appliance disposal. By 2029, ODS blowing agents are assumed to be phased out, resulting in no further ODP-weighted emissions. Table I-24 presents annual ODP emissions in the BAU through 2030.

Table I-24: ODP Emissions (ODP-weighted MT)

Year	BAU ODP Emissions
2010	38
2011	38
2012	41
2013	43
2014	43
2015	36
2016	23
2017	21
2018	21
2019	19
2020	17
2021	14
2022	12
2023	10
2024	8
2025	8
2026	8
2027	8
2028	8
2029	0
2030	0
Total 2010–2030	417

As shown, ODP emissions in the BAU are estimated at 417 ODP-weighted MT from 2010–2030.

GHG Emissions

Annual GHG emissions in the BAU are calculated based on assumptions detailed in Section I.5. Emissions in $MTCO_2eq$ are calculated based on the IPCC Second Assessment Report (SAR) and Third Assessment Report (TAR) global warming potentials (GWPs). Specifically, direct GHG emissions result from the release of foam-blowing agent at refrigerator EOL. Indirect GHG emissions result from transport and energy consumption during appliance dismantling.

Table I-25: Total Annual Emissions in the BAU in 2010 ($MTCO_2eq$)

Emissions Source	Summary Assumptions	Annual Emissions ($MT CO_2eq$)	Average Emissions per Appliance ($kg CO_2eq$)
Direct: Foam Blowing Agent	Loss assumptions presented in Section I.5.2	258,712	0.26
Indirect: Transport	Fuel efficiencies and emission factors shown in Table I-11	4,150	0.00
Indirect: Energy Consumption—Foam Handling	Auto shredder (0.06 kWh/appliance) and automated saw (5 kWh/appliance); at 0.751 $kgCO_2eq/kWh$	314	0.00
Total		263,176	0.27

As shown, total annual emissions in the BAU in 2010 are approximately 263,200 $MTCO_2eq$, almost all of which result from blowing agent losses. Per-appliance emissions are approximately 0.27 kg CO_2eq.

Total annual emissions in the BAU for 2010-2020 and 2010-2050 are shown in Table I-26. Direct emissions of blowing agent account for the vast majority of emissions.

Table I-26: Total Annual Emissions ($MTCO_2eq$) in the BAU (2010-2050)

Year	Direct Emissions: Foam Blowing Agent	Indirect Emissions:		Total Annual Emissions
		Energy Consumption for Foam Handling	Transport Fuel	
2010	258,712	314	4,150	263,176
2015	386,050	384	5,075	391,508
2020	396,450	362	4,792	401,604
2025	353,710	303	4,009	358,022
2030	286,267	224	2,969	289,460
2035	180,613	142	1,873	182,627
2040	69,440	54	720	70,215
2045	0	0	0	0
2050	0	0	0	0
2010–2020	3,914,196	3,995	52,857	3,971,048
2010–2050	9,074,097	8,280	109,544	9,191,921

Criteria Pollutant Emissions

Criteria pollutant emissions result from transport (fuel) and energy consumption during foam handling. Table I-27 presents criteria pollutant emissions associated with these activities in 2010.

Table I-27: Total Annual Criteria Pollutant Emissions (MT) in the BAU in 2010

Criteria Pollutant	Non Point: Transport	Point: Energy Consumption	Total Emissions
NO_x	11.39	0.49	11.89
PM10	0.31	0.43	0.74
PM2.5	0.06	0.11	0.17
SO_x	0.29	1.09	1.38

Table I-28 presents total annual criteria pollutant emissions associated with the BAU in 2010-2020 and 2010–2050.

Table I-28: Total Annual Criteria Pollutant Emissions (MT) in the BAU (2010-2050)

Year	NOx	PM10	PM2.5	SOx
2010	11.89	0.74	0.17	1.38
2015	14.53	0.91	0.21	1.68
2020	13.72	0.86	0.20	1.59
2025	11.48	0.72	0.17	1.33
2030	8.50	0.53	0.12	0.98
2035	5.36	0.33	0.08	0.62
2040	2.06	0.13	0.03	0.24
2045	—	—	—	—
2050	—	—	—	—
2010–2020	151.38	9.44	2.19	17.53
2010–2050	313.73	19.57	4.53	36.33

I.7.2. Scenario 1 Emissions

ODP Emissions Avoided

ODP emissions are avoided in Scenario 1 by reducing the total emissions of ODS blowing agent from 2010 to 2028. Beginning in 2029, all ODS blowing agents are assumed to be phased out. Table I-29 presents annual ODP-weighted emissions avoided in Scenario 1 through 2030.

Table I-29: ODP Emissions Avoided in Scenario 1

Year	ODP Emissions Avoided (ODP weighted MT)
2010	23.76
2011	23.50
2012	25.70
2013	27.10
2014	27.05
2015	22.24
2016	14.22
2017	13.36
2018	13.05
2019	11.72
2020	10.38
2021	8.57
2022	7.45
2023	6.32
2024	5.18
2025	5.21
2026	5.23
2027	5.26
2028	5.28
2029	—
2030	—
Total 2010–2030	260.58

As shown, ODP emissions avoided in Scenario 1 are approximately 261 ODP-weighted MT from 2010–2030. No ODP emissions are avoided beyond year 2028, as it is assumed that all ODS foam has been disposed by that year.

GHG Emissions Avoided

Annual GHG emissions avoided in Scenario 1 result from the removal and incineration of foam before blowing agent is released, and the elimination of energy consumption from foam shredding. No additional transport is required in this scenario. Because the additional foam removal is completed with manual saws (which require no energy), this does not significantly add to the scenario’s total emissions. Table I-30 presents the total annual emissions avoided in Scenario 1 in 2010.

Table I-30: Total Annual Emissions Avoided in Scenario 1 in 2010 ($MTCO_2eq$)

Emissions Source	Summary Assumptions	Annual Emissions Avoided (MT CO_2eq)	Average Emissions Avoided per Appliance (kg CO_2eq)
Direct: Foam Blowing Agent	Loss assumptions presented in Section I.5.2	165,022	0.17
Indirect: Transport	Fuel efficiencies and emission factors shown in Table I-11	—	—
Indirect: Energy Consumption—Foam Handling	Automated saw (5 kWh/appliance); at 0.751 $kgCO_2eq/kWh$	38	0.00
Total		165,060	0.17

As shown, total annual emissions avoided in Scenario 1 in 2010 are approximately 165,100 $MTCO_2eq$. Table I-31 presents total annual emissions avoided from 2010-2020 and 2010-2050. From 2010 to 2050, approximately 5.9 million $MTCO_2eq$ emissions are avoided in this scenario. The GHG benefits associated with foam removal decline sharply over time (reaching zero in 2043), as HCs and other low-GWP alternative blowing agents are assumed to penetrate the market (see Table I-5).

Table I-31: Total Annual Emissions Avoided ($MTCO_2eq$) in Scenario 1 (2010-2050)

Year	Direct Emissions: Foam Blowing Agent	Energy Consumption: Foam Handling	Transport	Total Annual Emissions Avoided
2010	165,022	38	—	165,060
2015	258,269	46	—	258,315
2020	256,296	43	—	256,340
2025	229,887	36	—	229,924
2030	187,323	27	—	187,350
2035	118,186	17	—	118,203
2040	45,439	7	—	45,446
2045	0	0	—	0
2050	0	0	—	0
2010–2020	2,549,655	478	—	2,550,133
2010–2050	5,911,499	991	—	5,912,491

Criteria Pollutant Emissions

Criteria pollutant emissions are calculated for transport and energy consumption from handling foam. Total transport in Scenario 1 is equal to the BAU, and therefore results in no incremental criteria pollutant emissions. Because energy consumption associated with handling foam in this scenario is lower than in the BAU, criteria pollutant emissions savings result. Table I-32 presents the savings associated with these activities in 2010.

Table I-32: Total Annual Incremental Criteria Pollutant Emissions (MT) in Scenario 1 in 2010

Criteria Pollutant	Non Point: Transport	Point: Energy Consumption	Total Emissions
NOx	—	(0.06)	(0.06)
PM10	—	(0.05)	(0.05)
PM2.5	—	(0.01)	(0.01)
SOx	—	(0.13)	(0.13)

Table I-33 presents total annual incremental criteria pollutant emissions associated with Scenario 1 in 2010-2020 and 2010- 2050. As shown, this scenario results in emissions savings of 1.6 MT NO_x, 1.4 MT PM10, 0.4 MT PM2.5, and 3.4 MT SO_x from 2010 to 2050.

Table I-33: Total Annual Incremental Criteria Pollutant Emissions (MT) in Scenario 1 (2010-2050)

Year	NOx	PM10	PM2.5	SOx
2010	(0.06)	(0.05)	(0.01)	(0.13)
2015	(0.07)	(0.06)	(0.02)	(0.16)
2020	(0.07)	(0.06)	(0.02)	(0.15)
2025	(0.06)	(0.05)	(0.01)	(0.13)
2030	(0.04)	(0.04)	(0.01)	(0.09)
2035	(0.03)	(0.02)	(0.01)	(0.06)
2040	(0.01)	(0.01)	(0.00)	(0.02)
2045	—	—	—	—
2050	—	—	—	—
2010–2020	(0.75)	(0.65)	(0.17)	(1.66)
2010–2050	(1.55)	(1.35)	(0.36)	(3.43)

I.7.3. Scenario 2 Emissions

ODP Emissions Avoided

ODP emissions are avoided in Scenario 2 by reducing the total emissions of ODS blowing agent from 2010 to 2028. Beginning in 2029, all ODS blowing agents are assumed to be phased out. Emissions avoided in Scenario 2 are equal to those avoided in Scenario 1 because it is assumed that manual foam removal with handheld and automated saws result in the same blowing agent emissions savings. As shown in Table I-29, ODP emissions avoided in Scenario 2 are approximately 261 ODP-weighted MT from 2010-2030.

GHG Emissions Avoided

Annual GHG emissions avoided in Scenario 2 result from the removal and incineration of foam before blowing agent is released. Additional transport of appliances to DARs instead of CARs, and increased energy consumption of the automated saws during foam handling partially offset these emissions reductions. Table I-34 presents the total annual emissions avoided in Scenario 2 in 2010.

Table I-34: Total Annual Emissions Avoided in Scenario 2 in 2010 ($MTCO_2eq$)

Emissions Source	Summary Assumptions	Annual Emissions	Average Emissions per Appliance ($kgCO_2eq$)
Direct: Foam Blowing Agent	Loss assumptions presented in Section I.5.2	165,022	0.17
Indirect: Transport	Fuel efficiencies and emission factors shown in Table I-11	(3,940)	(0.00)
Indirect: Energy Consumption—Foam Handling	Automated saw (5 kWh/appliance); at 0.751 $kgCO_2eq$/kWh	(1,527)	(0.00)
Total		159,556	0.16

As shown, total annual emissions avoided in Scenario 2 in 2010 are nearly 159,600 $MTCO_2eq$. Table I-35 presents total annual emissions avoided from 2010-2020 and 2010-2050. From 2010 to 2050, approximately 5.8 million $MTCO_2eq$ emissions are avoided in this scenario. The GHG benefits associated with foam removal decline sharply over time (reaching zero in 2043), as HCs and other low-GWP alternative blowing agents are assumed to penetrate the market.

Table I-35: Total Annual Emissions Avoided ($MTCO_2eq$) in Scenario 2 (2010-2050)

Year	Direct Emissions: Foam Blowing Agent	Indirect Emissions: Energy Consumption for Foam Handling	Indirect Emissions: Transport Fuel	Total Annual Emissions Avoided
2010	165,022	(1,527)	(3,940)	159,556
2015	258,269	(1,867)	(4,818)	251,584
2020	256,296	(1,763)	(4,549)	249,984
2025	229,887	(1,475)	(3,806)	224,606
2030	187,323	(1,092)	(2,818)	183,412
2035	118,186	(689)	(1,778)	115,719
2040	45,439	(265)	(684)	44,490
2045	0	0	0	0
2050	0	0	0	0
2010–2020	2,549,655	(19,450)	(50,180)	2,480,024
2010–2050	5,911,499	(40,310)	(103,996)	5,767,194

Criteria Pollutant Emissions

Criteria pollutant emissions are calculated for transport and energy consumption from handling foam. Additional transport of appliances to DARs instead of CARs and increased energy consumption from automated saws during foam removal result in incremental criteria pollutant emissions in Scenario 2. Table I-36 presents the incremental emissions associated with these activities in 2010.

Table I-36: Total Annual Criteria Pollutant Emissions (MT) in Scenario 2 in 2010

Criteria Pollutant	Non Point: Transport	Point: Energy Consumption	Total Emissions
NOx	11.34	2.39	13.72
PM10	0.31	2.08	2.39
PM2.5	0.06	0.55	0.61
SOx	0.29	5.29	5.58

Table I-37 presents total annual incremental criteria pollutant emissions associated with Scenario 2 in 2010-2020 and through 2050. As shown, this scenario results in incremental emissions of roughly 362 MT NO_x, 63 MT PM10, 16 MT PM2.5, and 147 MT SO_x from 2010 to 2050.

Table I-37: Total Annual Incremental Criteria Pollutant Emissions (MT) in Scenario 2 (2010–2050)

Year	NOx	PM10	PM2.5	SOx
2010	13.72	2.39	0.61	5.58
2015	16.78	2.93	0.75	6.82
2020	15.85	2.76	0.71	6.44
2025	13.26	2.31	0.59	5.39
2030	9.82	1.71	0.44	3.99
2035	6.19	1.08	0.28	2.52
2040	2.38	0.42	0.11	0.97
2045	—	—	—	—
2050	—	—	—	—
2010–2020	174.80	30.50	7.80	71.03
2010–2050	362.27	63.20	16.17	147.20

I.7.4. Scenario 3 Emissions

ODP Emissions Avoided

ODP emissions are avoided from 2010-2028 in Scenario 3 by reducing the total emissions of ODS blowing agent. Beginning in 2029, all units containing ODS blowing agents are assumed to have reached disposal. Table I-38 presents annual ODP-weighted emissions avoided in Scenario 3 through 2030.

Table I-38: ODP Emissions Avoided (ODP-weighted MT)

Year	Scenario 3 ODP Emissions Avoided
2010	33.29
2011	32.93
2012	36.01
2013	37.98
2014	37.90
2015	31.16
2016	19.93
2017	18.72
2018	18.28
2019	16.43
2020	14.55
2021	12.01
2022	10.44
2023	8.86
2024	7.26
2025	7.29
2026	7.33
2027	7.37
2028	7.40
2029	—
2030	—
Total 2010–2030	365.10

As shown, total ODP emissions avoided in Scenario 3 are approximately 365 ODP-weighted MT from 2010–2030.

GHG Emissions Avoided

Annual GHG emissions avoided in Scenario 3 result from the removal and incineration of foam before blowing agent is released. Additional transport of appliances to DARs instead of CARs and increased energy consumption of the fully automated appliance dismantlers during foam handling partially offset these emissions reductions. Table I-39 presents the total annual emissions avoided in Scenario 3 in 2010.

Table I-39: Total Annual Emissions Avoided in Scenario 3 in 2010 ($MTCO_2eq$)

Emissions Source	Summary Assumptions	Annual Emissions	Average Emissions per Appliance ($kgCO_2eq$)
Direct: Foam Blowing Agent	Loss assumptions presented in Section I.5.2	227,607	0.23
Indirect: Transport	Fuel efficiencies and emission factors shown in Table I-11	(4,369)	(0.00)
Indirect: Energy Consumption—Foam Handling	Fully automated appliance dismantler (17.5 kWh/appliance); at 0.751 $kgCO_2eq/kWh$	(12,572)	(0.01)
Total		210,666	0.22

As shown, total annual emissions avoided in Scenario 3 in 2010 are nearly 210,700 $MTCO_2eq$. Table I-40 presents total annual emissions avoided from 2010-2020 and through 2050. From 2010 to 2050, approximately 7.6 million $MTCO_2eq$ emissions are avoided in this scenario. The GHG benefits associated with foam removal decline sharply over time (reaching zero in 2043), as HCs and other low-GWP alternative blowing agents are assumed to penetrate the market.

Table I-40: Total Annual Emissions Avoided ($MTCO_2eq$) in Scenario 3 (2010-2050)

Year	Direct Emissions: Foam Blowing Agent	Energy Consumption: Foam Handling	Transport	Total Annual Emissions Avoided
2010	227,607	(12,572)	(4,369)	210,666
2015	343,625	(15,373)	(5,342)	322,910
2020	349,918	(14,515)	(5,044)	330,358
2025	312,600	(12,145)	(4,221)	296,234
2030	253,417	(8,993)	(3,125)	241,299
2035	159,887	(5,674)	(1,972)	152,241
2040	61,472	(2,181)	(758)	58,532
2045	0	0	0	0
2050	0	0	0	0
2010–2020	3,461,157	(160,123)	(55,647)	3,245,387
2010–2050	8,024,090	(331,848)	(115,325)	7,576,917

Criteria Pollutant Emissions

Criteria pollutant emissions are calculated for transport and energy consumption from handling foam. Additional transport of appliances to DARs instead of CARs and increased energy consumption of fully automated appliance dismantlers during foam handling result in incremental criteria pollutant emissions in Scenario 3. Table I-41 presents the incremental emissions associated with these activities in 2010.

Table I-41: Total Annual Criteria Pollutant Emissions (MT) in Scenario 3 in 2010

Criteria Pollutant	Non Point: Transport	Point: Energy Consumption	Total Emissions
NOx	13.42	19.67	33.08
PM10	0.37	17.14	17.51
PM2.5	0.07	4.57	4.64
SOx	0.34	43.53	43.88

Table I-42 presents total annual incremental criteria pollutant emissions associated with Scenario 3 in 2010-2020 and 2050. As shown, this scenario results in incremental emissions of 873 MT NO_x, 462 MT PM10, 122 MT PM2.5, and 1,158 MT SO_x from 2010 to 2050.

Table I-42: Total Annual Incremental Criteria Pollutant Emissions (MT) in Scenario 3 (2010-2020, 2050)

Year	NOx	PM10	PM2.5	SOx
2010	33.08	17.51	4.64	43.88
2015	40.46	21.41	5.67	53.65
2020	38.20	20.22	5.35	50.66
2025	31.96	16.92	4.48	42.39
2030	23.67	12.53	3.32	31.39
2035	14.93	7.90	2.09	19.80
2040	5.74	3.04	0.80	7.61
2045	—	—	—	—
2050	—	—	—	—
2010–2020	421.40	223.04	59.06	558.83
2010–2050	873.33	462.25	122.40	1,158.15

I.8. Summary of Costs and Benefits

This section summarizes the incremental costs and benefits of each scenario relative to the baseline, as well as the cost-effectiveness in terms of \$/MTCO$_2$eq.

I.8.1. Incremental Costs

Table I-43 presents the total annual per-unit costs and incremental costs by scenario. It should be noted that, while metal recycling and refrigerant recovery are considered outside the boundary of this analysis, it is estimated that these activities result in per-unit cost *savings* of approximately \$20.[41] Table I-43 also presents per-unit costs including this \$20 cost savings. As shown, incremental costs associated with Scenario 1 are significantly lower than those associated with Scenarios 2 and 3, due primarily to the additional transport, O&M, and facility rental and equipment purchase costs associated with appliance processing at DARs. Relatively high energy consumption costs associated with using a fully automated appliance dismantling machine in Scenario 3 are outweighed by the relatively lower labor costs associated with foam removal in this scenario.

Review of Regulatory Scenarios Assessed

- Scenario 1: DARs and CARs recycle appliances using manual foam removal techniques.
- Scenario 2: DARs recycle appliances using manual foam removal techniques.
- Scenario 3: DARs recycle appliance using fully automated appliance dismantlers.

Table I-43: Incremental Costs per Unit[a]

Activity or Stage	Costs (\$)			
	BAU	Scenario 1	Scenario 2	Scenario 3
Foam handling	\$2.47	\$16.00	\$16.00	\$4.80
Energy	\$0.05	\$0.04	\$0.28	\$1.93
Transport (labor and fuel)	\$4.95	\$4.95	\$9.63	\$9.96
Foam Disposal Fees	\$1.26	\$4.83	\$4.83	\$5.79
O&M Costs	\$3.09	\$3.09	\$20.00	\$20.00
Capital Costs (Annualized): Facility Rental and Equipment Purchase[a]	\$0.00	\$0.34	\$4.09	\$6.08
Total Per-unit Costs	\$11.82	\$29.26	\$54.83	\$48.55
Estimated total per-unit costs including metal recycling and refrigerant recovery[b]	(\$8.37)	\$9.07	\$34.64	\$28.36
Total Incremental Per-unit Costs	NA	\$17.44	\$43.01	\$36.73

[a] For Scenarios 2 and 3, capital costs shown here are for 2010 and are developed based on annual facility throughput; per-unit costs will increase in later years as facility throughput declines (as the number of units containing high-GWP blowing agents decreases) but capital costs (e.g., facility lease) remain fixed.
[b] The value of used metals is estimated at \$21/unit, while refrigerant recovery is estimated to cost \$0.81/unit (ARC 2010).

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[41] The value of used metals is estimated at \$21/unit, while refrigerant recovery is estimated to cost only \$0.81/unit (ARC 2010).

Table I-44 presents the total incremental annual and capital costs based on the assumed number of units containing high-GWP blowing agents reaching EOL each year. It should be noted that the costs shown here could be offset, at least in part, if carbon credits are earned for the destruction of ODS blowing agents, per the Climate Action Reserve protocol. As discussed in section 0, approximately $3.15/unit can be earned assuming a price of $10/MTCO$_2$eq.[42]

Table I-44: Total Incremental Costs ($) by Scenario, 2010-2050

Year	Total Incremental ODS Costsa			Total Incremental HFC Costsa			Total Incremental Costs (ODS and HFCs)		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
2010–2050 NPV	140,885,191	346,647,167	314,195,325	129,359,370	325,874,196	281,798,378	270,244,560	672,521,363	595,993,703

[a] Total annual costs by component are shown in Appendix B.

I.8.2. Incremental Benefits

ODP Benefits

Table I-45 presents the ODP-weighted emissions avoided in Scenarios 1, 2, and 3. ODP emissions savings occur through 2028, after which point all units containing ODS blowing agents (HCFC-141b) are assumed to have reached retirement.

Table I-45: Emissions Avoided (ODP-weighted MT)

Year	Scenario 1	Scenario 2	Scenario 3
2010	23.76	23.76	33.29
2015	22.24	22.24	31.16
2020	10.38	10.38	14.55
2025	5.21	5.21	7.29
2028	5.28	5.28	7.40
2030	—	—	—
Total 2010–2030	260.6	260.6	365.1

As shown, ODP emissions benefits from Scenarios 1 and 2 are equivalent because it is assumed that all manual foam removal techniques result in the same quantity of emissions. Scenario 3 offers additional savings, as emissions of blowing agent during automated foam removal are significantly lower. Figure I-8 graphically depicts the emissions avoided for each scenario from 2010 to 2030.

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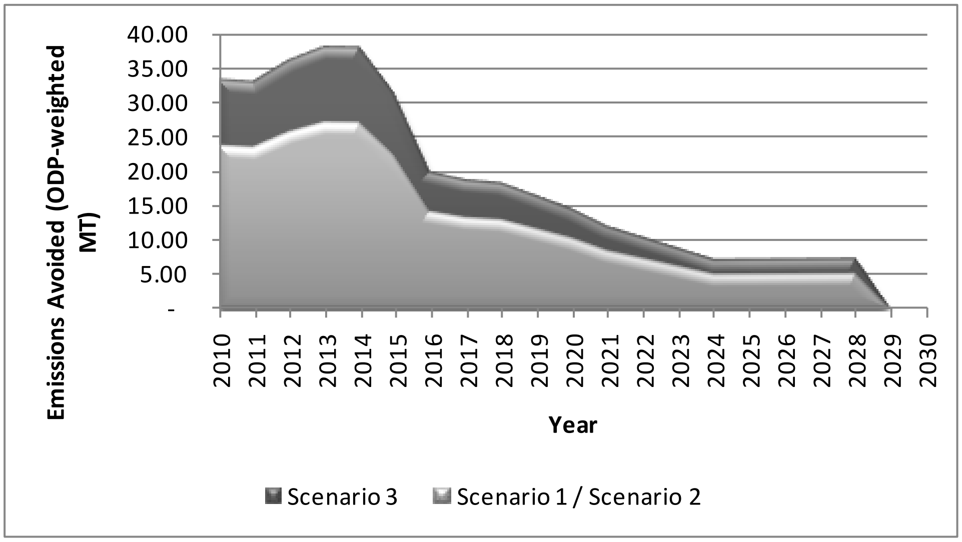
[42] This value assumes a 50% CO$_2$e discounting for BAU emissions avoided in landfill but does not include discounting associated with transport and destruction, nor does it account for project costs (e.g., registration, administration, verification, measurements, reporting, etc.) which would lower total value.

Figure I-8: ODP-Weighted Emissions Avoided, 2010-2030



GHG Benefits

Table I-46 and Table I-47 present the incremental emissions avoided for Scenarios 1, 2, and 3 relative to the baseline for years 2010-2020 and 2010-2050 by emissions source. As shown, blowing agent losses account for the vast majority of GHG emissions associated with appliance disposal. Indeed, the large reductions in emissions under each management scenario are almost entirely due to reduced blowing agent losses at disposal. Annual emissions avoided in Scenario 3 are significantly greater than in Scenarios 1 and 2, due to the use of fully automated appliance machines instead of manual foam removal practices. Emissions reductions are lowest in Scenario 2 since fewer direct GHG emissions are avoided from foam capture/destruction compared to Scenario 3, and indirect GHG emissions are greater than in Scenario 1 due to the use of automated rather than handheld saws, as well as increased transport. Conversely, the higher transport and energy consumption in Scenario 3 are offset by greater emissions reductions from blowing agent losses. All units containing ODS and HFC blowing agents are assumed to reach full retirement by 2042, after which point no environmental benefits are realized or costs incurred.

It should be underscored that there is great uncertainty associated with the avoidance of emissions from landfills (see Section I.5.2 and I.14). If emissions in the BAU are not avoided due to bioremediation, sorption, and landfill gas combustion—as assumed in this analysis—GHG emission reductions in each scenario would more than double those presented in Table I-46 and Table I-47. For example, in 2020, HFC emissions avoided in Scenario 3 would be approximately 0.5 MMTCO_2eq, instead of 0.2 MMTCO_2eq.

Table I-46: Total Annual Direct and Indirect Emissions Avoided for Each Scenario (MTCO$_2$eq)

Year	Direct (Foam) Emissions Avoided						Indirect Emissions Avoided from Energy and Transport[a]					
	ODS			HFCs			To Process ODS Units			To Process HFC Units		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
2010	151,207	151,207	211,861	13,816	13,816	15,745	37	(5,358)	(16,602)	1	(109)	(339)
2015	141,502	141,502	198,263	116,767	116,767	145,362	34	(5,014)	(15,536)	11	(1,671)	(5,179)
2020	66,061	66,061	92,560	190,236	190,236	257,358	16	(2,341)	(7,253)	27	(3,971)	(12,307)
2025	33,124	33,124	46,411	196,764	196,764	266,189	8	(1,174)	(3,637)	28	(4,108)	(12,729)
2030	0	0	0	187,323	187,323	253,417	0	0	0	27	(3,911)	(12,118)
2035	0	0	0	118,186	118,186	159,887	0	0	0	17	(2,467)	(7,646)
2040	0	0	0	45,439	45,439	61,472	0	0	0	7	(949)	(2,940)
2045	0	0	0	0	0	0	0	0	0	0	0	0
2050	0	0	0	0	0	0	0	0	0	0	0	0
2010–2050	1,658,205	1,658,205	2,323,373	4,253,294	4,253,294	5,700,716	404	(58,753)	(182,063)	588	(85,552)	(265,109)

[a] Negative values (shown in parentheses) reflect additional emissions, not emission savings. Appendix B presents the annual indirect emissions avoided disaggregated by energy and transport.

Table I-47: Total Emissions Avoided for Each Scenario (MTCO$_2$eq)

Year	Emissions Avoided to Process ODS Units			Emissions Avoided to Process HFC Units			Total Emissions Avoided (ODS+HFCs)		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
2010	151,243	145,849	195,259	13,817	13,706	15,407	165,060	159,556	210,666
2015	141,536	136,488	182,727	116,779	115,096	140,183	258,315	251,584	322,910
2020	66,077	63,720	85,307	190,263	186,264	245,051	256,340	249,984	330,358
2025	33,132	31,950	42,774	196,792	192,656	253,460	229,924	224,606	296,234
2030	0	0	0	187,350	183,412	241,299	187,350	183,412	241,299
2035	0	0	0	118,203	115,719	152,241	118,203	115,719	152,241
2040	0	0	0	45,446	44,490	58,532	45,446	44,490	58,532
2045	0	0	0	0	0	0	0	0	0
2050	0	0	0	0	0	0	0	0	0
2010–2050	1,658,609	1,599,452	2,141,310	4,253,882	4,167,742	5,435,607	5,912,491	5,767,194	7,576,917

Figure IV-2 graphically compares the cumulative GHG emissions avoided in each scenario from 2010 to 2050. Scenario 3 results in the greatest GHG emissions savings over both short and long time periods. Emissions savings in each scenario are due primarily to the avoided blowing agent emissions. However, due to the transition from ODS and HFC blowing agents to HCs, Scenarios 2 and 3 will eventually result in net incremental emissions from transport and energy consumption, rather than emissions savings.

Figure I-9: Cumulative Net GHG Emissions Avoided (MMTCO$_2$eq) 2010-2050

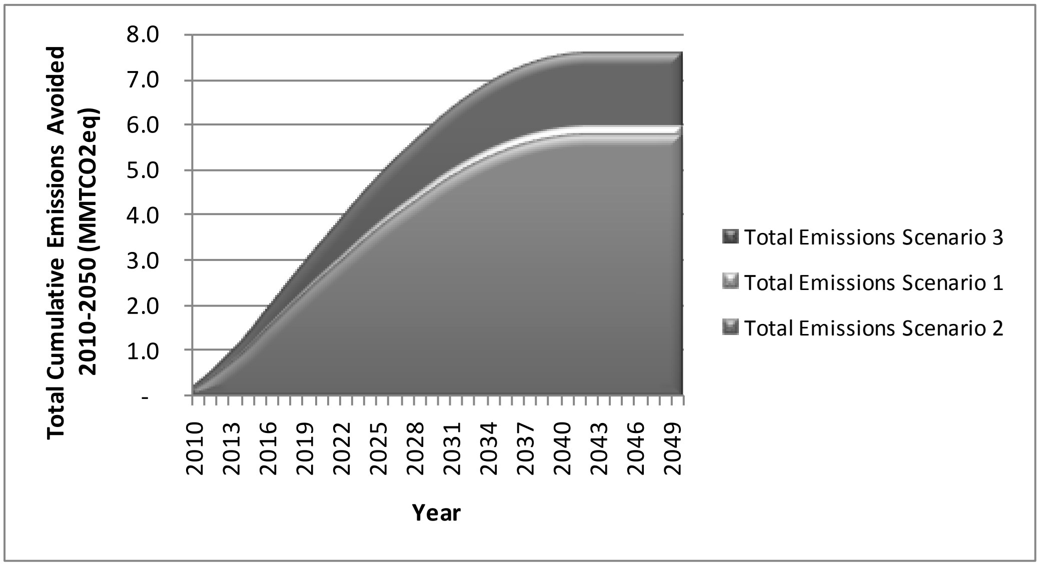
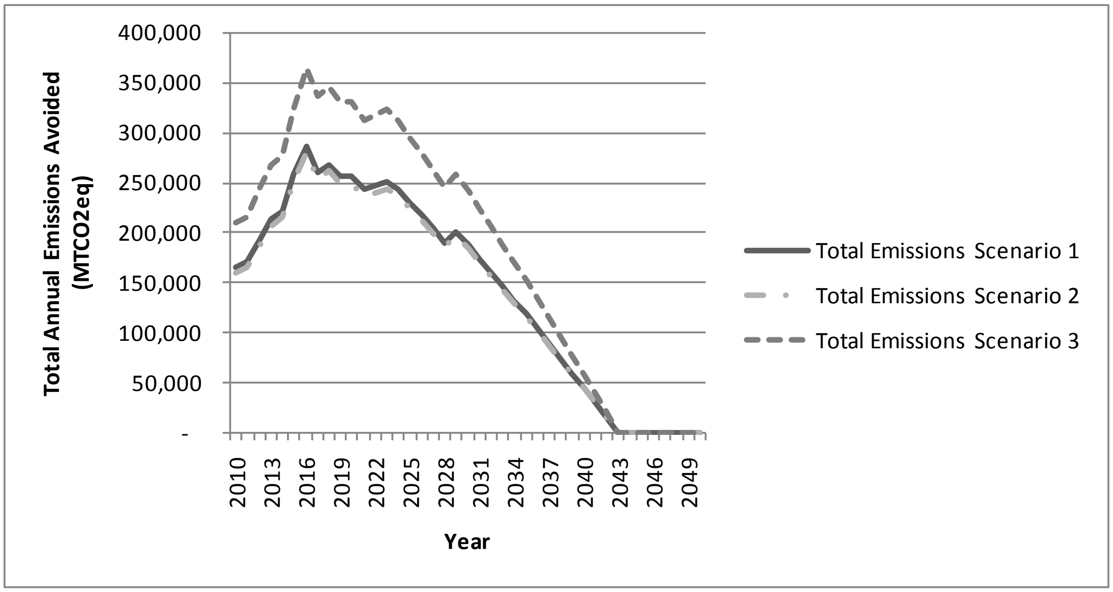


Figure IV-3 compares the annual GHG emissions avoided in each scenario from 2010 to 2050.

Figure I-10: Total Annual GHG Emissions Avoided (MTCO$_2$eq) 2010-2050



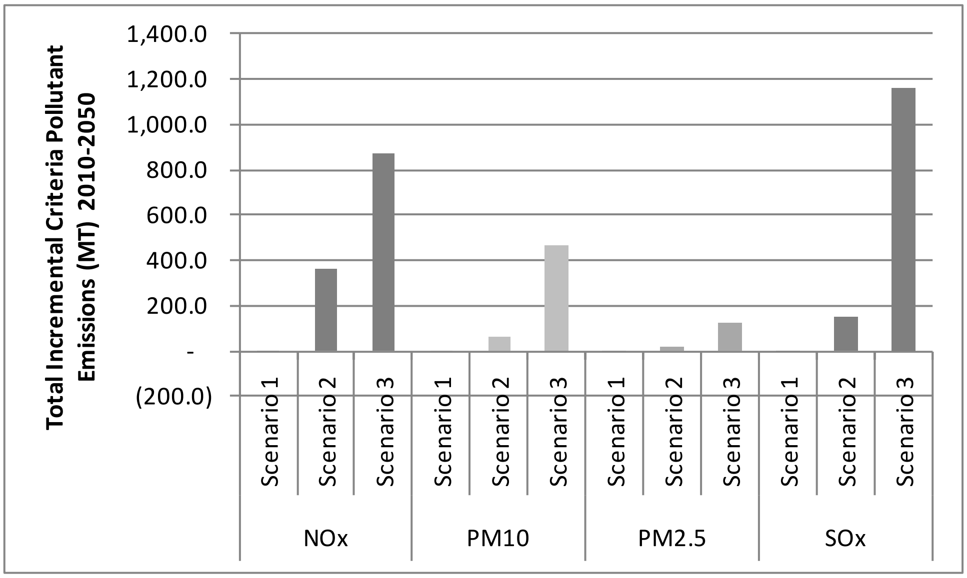
I.8.3. Incremental Criteria Pollutants

Criteria pollutant emissions are calculated for transport (non-point source) and energy consumption (point source) associated with foam handling. Scenario 1 is assumed to require the same transport as the BAU, and therefore results in no incremental non-point criteria pollutant emissions. In addition, energy consumption in Scenario 1 is lower than in the BAU because of the elimination of foam shredding. However, in Scenarios 2 and 3, transport to DARs instead of CARs and energy consumption from foam handling are higher than in the BAU due to the use of automated saws and fully automated appliance dismantlers. In Scenario 3, transport distances are even larger due to the distance traveled to and from blowing agent destruction facilities. Consequently, Scenario 3 results in the largest incremental criteria pollutants.

However, it is important to note that incremental pollutant emissions from non-point (transport) in Scenario 3 is assumed to primarily be emitted between California and Utah, where the blowing agent is destroyed. Moreover, the incremental criteria pollutant emissions from point sources under Scenarios 2 and 3 in the near-term are not significant;[43] SO_x emissions account for the greatest incremental criteria pollutant emissions, particularly in Scenario 3. However, in this scenario these emissions occur at a minimum of eight facilities throughout California. Therefore, incremental emissions of criteria pollutants from a single point-source are no higher than 2.5 MT SO_x in 2010, and reach a peak at 2.7 MT SO_x in 2016. Appendix B presents detailed tables of annual incremental criteria pollutant emissions in each scenario.

Figure I-11 graphically presents the total cumulative criteria pollutant emissions from 2010-2050 associated with each management scenario.

Figure I-11: Total Incremental Criteria Pollutant Emissions 2010-2050 (MT)



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[43] A "major stationary source," as defined in Section 112 of the Federal Clean Air Act, is one with the potential to emit 10 tons per year, or more, of any hazardous air pollutant listed pursuant to Section 112(b) of the Federal Clean Air Act; or 25 tons per year, or more, of any combination of hazardous air pollutants listed pursuant to Section 112(b) of the Federal Clean Air Act. According to ARB's "Authority to Construct" definitions, a major stationary source may also be one with a potential to emit more than: 25 tons per year of nitrogen oxides, 25 tons per year of volatile organic compounds, 100 tons per year of sulfur dioxide, 100 tons per year of carbon monoxide, 100 tons per year of PM10, or 100 tons per year of a regulated air pollutant.

I.8.4. Cost Effectiveness

The incremental costs per GHG emission reduction of each management scenario are presented in Table I-48. Beyond 2042, all ODS and HFC blowing agents are assumed to be phased out. Therefore, no emissions reductions or costs result in these years. By 2050, Scenario 1 is projected to reduce ODS and HFC emissions equivalent to 5.9 million $MTCO_2eq$ at \$46/$MTCO_2eq$; Scenario 2 is projected to reduce 5.8 million $MTCO_2eq$ at \$117/$MTCO_2eq$; and Scenario 3 is projected to reduce 7.6 million $MTCO_2eq$ at \$79/$MTCO_2eq$. The incremental cost of reducing GHG emissions from the recovery of ODS foam is higher than that for that of HFCs due to the fact that by 2010, all units containing CFC blowing agents are assumed to have reached full retirement, meaning that only HCFC-141b blowing agents—with a GWP of only 700 (compared to 950 for HFC-245fa and 1300 for HFC-134a)—is available at equipment EOL. However, it should be noted that costs shown here do not account for any potential carbon offset credits which may be earned for the destruction of ODS appliance foam (see section 0 for more details). More importantly, it should be noted that the cost-effectiveness of foam recovery/destruction from refrigerators/freezers is significantly lower if less optimistic landfill scenarios are assumed in the analysis; indeed, assuming no long-term emission avoided in landfills (from bioremediation/landfill gas recovery systems), the cost to reduce GHG emissions would be less than half the amount shown below for HFC units (\$11/$MTCO_2eq$ from 2010-2020 in Scenario 1, \$26/$MTCO_2eq$ for Scenario 2, and \$22/$MTCO_2eq$ for Scenario 3).

Table I-48: Incremental \$/$MTCO_2eq$ Avoided 2010-2020, 2010-2050[a]

Year	Cost Effectiveness for ODS Emissions Avoided			Cost Effectiveness for HFC Emissions Avoided			Total Cost Effectiveness (ODS+HFCs)		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
2010-2020 NPV	\$106	\$270	\$185	\$23	\$58	\$42	\$67	\$170	\$119
2010-2050 NPV	\$85	\$217	\$147	\$30	\$78	\$52	\$46	\$117	\$79

[a] Costs are in present value (at 5% discount rate).

I.9. Discussion of Findings

Table I-49 summarizes the estimated total costs, GHG emissions avoided, and average cost per $MMTCO_2eq$ avoided from 2010- 2020 and 2010- 2050 across the three alternative management scenarios.

Table I-49: Total Incremental Costs and GHG Emissions Avoided by Scenario

Total Costs and GHG Emissions Avoided	2010 2020			2010 2050		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
NPV Incremental Cost (\$ millions)	\$ 171	\$ 421	\$ 387	\$ 270	\$ 673	\$ 596
GHG Emissions Avoided ($MMTCO_2eq$)	2.6	2.5	3.2	5.9	5.8	7.6
Average Cost per $MTCO_2eq$ Avoided	\$ 67	\$ 170	\$ 119	\$46	\$117	\$79

As shown, each management scenario examined in this analysis results in significant GHG emission savings from 2010-2042 by reducing emissions of foam blowing agent. However, once HC/low-GWP blowing agents have fully penetrated the appliance market and reach retirement, emissions savings from foam recovery and destruction will be insignificant.

In addition, one may want to compare the average cost per $MTCO_2eq$ avoided by reducing emissions of foam blowing agents in refrigerators with the average cost per $MTCO_2eq$ avoided for other climate change measures in order to compare the cost vs. benefit of this GHG emissions reduction approach with that of others in different industries or sectors. Table I-50 presents the estimated emission reductions and cost-effectiveness of various proposed AB 32 climate change measures (cost estimates are from the 2008 [AB 32] Scoping Plan) (ARB 2008b), with measures listed from the most to least cost-effective. Cost bracketed by parentheses ($xx) indicate a negative cost, or cost savings. For comparison, the estimated price for purchasing $MTCO_2eq$ reduction credits on the voluntary carbon market in California has been provided. ARB has estimated the price of carbon reductions from cap and trade at $20–$40 $MTCO_2eq$ (ARB 2010), although a Reuters analysis estimates that the carbon price will begin at $13/$MTCO_2eq$ in 2012 (assuming a Cap and Trade program begins in 2012), eventually increasing to $70/$MTCO_2eq$ by 2020 (Reuters 2011). Note that any estimated cost of the cap and trade program may vary greatly from original estimated costs, depending on market forces.

Table I-50: Potential GHG Emission Reductions from Various Climate Change Measures[a]

Climate Change Measure (proposed or adopted)	Potential 2020 Reductions $MMTCO_2eq$	Cost of Reduction $/$MTCO_2eq$
Refinery flare recovery	0.33	($119.70)
Energy efficiency (electricity and natural gas)	19.5	($109.40)
Leak reduction from oil and gas transmission	0.9	($18.90)
Carbon intensity standard for cement manufacturing	1.9	($1.80)
SF6 leak reduction and recycling in electrical applications	0.1	($1.00)
Stationary Refrigerant Management Program	5.8	($0.60)
Limit High-GWP use in consumer products	0.25	$0.25
Low-GWP refrigerants for motor vehicles	2.5	$6.32
Landfill gas control measure	1.5	$8.64
Sustainable forests	5.0	$10.00
Small containers of refrigerant (deposit and return of cans containing less than two pounds refrigerant)	0.26	$11.54
High-GWP reduction in semiconductor manufacturing	0.15	$17.00
Alternative suppressants in fire protection systems	0.10	$18.00
Cap and Trade for large industrial sources	74.6	$20.00–$40.00
Removal of methane exemption from existing refinery regulations	0.014	$40.70
Foam GHG recovery and destruction from residential appliances (HFC+ODS)	0.26- 0.33	$76.96- $233.53[b]
Renewables portfolio standard (renewable energy)	21.3	$133.00
Methane capture at large dairies (voluntary)	1.0	$156.00

[a] This is not a complete listing of all AB 32 Climate Measures; a complete list can be found at http://www.arb.ca.gov/cc/scopingplan/sp_measures_implementation_timeline.pdf.

[b] 2020 costs are not discounted.

For comparative purposes, the overall GHG emission reduction goal of AB 32 is to reduce GHG emissions by 174 $MMTCO_2eq$ from projected business as usual 2020 emissions (600 $MMTCO_2eq$) in order to meet the 1990 GHG emission baseline levels of 427 $MMTCO_2eq$ (ARB 2007). A foam recovery and destruction program emission reduction of 0.33 $MMCO_2eq$ represents 0.2% of the total reduction goal.

I.9.1. Scope of Work Limitations

Refrigerant recovery and destruction from residential refrigerator-freezers was purposely excluded from this LCA because existing federal and state regulations already require the proper removal and management of refrigerant from appliances prior to recycling or disposal. The California Department of Toxic Substances Control (DTSC) oversees the Certified Appliance Recycler (CAR) program, which requires that any entity recycling or disposing of an appliance that has reached end-of-life must recover all refrigerant from the appliance (additional details of the CAR program are included in the following section, “Background”). However, actual data on recovered refrigerant at the CAR level is not reported to DTSC, which makes it difficult to assess the actual success of the regulations in reducing refrigerant emissions from end-of-life (EOL) appliances.

It should be noted that in compliance with the (Clean Air Act) Section 608 Refrigerant Recycling Rule, reclaimers do report refrigerant reclamation information to the U.S. EPA. According to the U.S. EPA Web page, *Complying With The Section 608 Refrigerant Recycling Rule*:[44]

> "Reclaimers must maintain records of the names and addresses of persons sending them material for reclamation and the quantity of material sent to them for reclamation. This information must be maintained on a transactional basis. Within 30 days of the end of the calendar year, reclaimers must report to EPA the total quantity of material sent to them that year for reclamation, the mass of refrigerant reclaimed that year, and the mass of waste products generated that year."

However, the information reported by reclaimers is not detailed enough to track the amount of refrigerant recovered by individual CARs, as the refrigerant reclaimed is aggregated by refrigerant type and amount, and not disaggregated by amount collected from each individual recovery site.

Because of the time, effort, and cost associated with recovering (and subsequently reclaiming or destroying) small amounts of refrigerant from household appliances, some disincentives to compliance are at play. Anecdotal evidence suggests that not all refrigerant is properly recovered from EOL appliances, although it is difficult to assess actual compliance levels. The environmental implications of low compliance with existing refrigerant recovery requirements may be significant; with an estimated one million residential refrigerator-freezers reaching EOL each year in California, and each of these appliances containing on average 0.3 - 0.5 lbs. of HFC-134a, potential annual emissions of refrigerant are 300,000 - 500,000 lbs. of HFC-134a, equivalent to 0.2 - 0.3 MMTCO$_2$eq. It may be of interest to the ARB or the California Department of Toxic Substances Control (DTSC) to conduct a study on compliance rates to determine if emissions from EOL appliances (and other refrigerant-containing equipment) are indeed significant, and if so, to then determine the cost-benefit of additional or alternative enforcement strategies.

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[44] See http://www.epa.gov/ozone/title6/608/608fact.html.

I.10. Recommendations

Due to the limited scope of this research project, a number of simplifications were made in this analysis. A more complete LCA would require additional considerations and a more nuanced methodology. These considerations include:

- Not all costs and cost *savings* associated with appliance recycling/disposal were considered within the project boundary: the cost savings associated with the value of used metals (on the recycling market) would effectively reduce average per unit costs by roughly $20 in all management scenarios considered.
- Non-compliance with current refrigerant recovery regulations: to the extent that full compliance is not occurring in the baseline, additional GHG emission reductions may be possible. Cost savings may also be possible, to the extent that recovered refrigerant is reclaimed for resale.
- Uncertainty associated with the future market penetration of alternative blowing agents: this analysis assumes an aggressive penetration of low-GWP blowing agents over time, but a less aggressive replacement rate of HFC blowing agents in new units will result in prolonged climate benefits associated with foam recovery and destruction at appliance EOL.
- Appliance foam recovery and destruction in rural versus urban regions of California: dedicated appliance recycling facilities will be more economically viable in more densely populated areas.
- Technical barriers potentially associated with the recovery of HCFC (in lieu of CFC) blowing agent using fully automated appliance technologies: anecdotal evidence suggests that high equipment corrosion may occur.
- Changes in energy prices over time: this analysis assumes a constant energy price over time, which likely underestimates costs associated with this source.
- Impact of the voluntary carbon market on increasing baseline foam recovery rates into the future: the Climate Action Reserve approved an ODS destruction protocol on February 3, 2010, and such destruction will be eligible for offsets under California's cap and trade program, set to begin in January 2012. Future protocols may allow for the destruction of HFC blowing agents.
- Relative impact of emission reductions using updated GWP values (based on IPCC AR4) in lieu of SAR/TAR.[1]

Further, the following additional considerations that could not be fully researched to determine their costs and benefits are discussed qualitatively below, because of their potential impact on the cost and feasibility of any foam recovery and destruction management scenario:

- Unintended consequences of regulating foam recovery from appliances;
- New technologies at landfill/auto shredders for recovering foam expansion agents; and
- Potential phase-down of HFCs in insulating foam.

These issues are described further below.

I.10.1. Unintended Consequences of Regulating Foam Recovery from Appliances

Although outside the scope of work of this particular research project, the implications of the shift in appliance recycling in California from a commodity model to a service model is unclear but may be significant, potentially resulting in a reduced incentive to recycle refrigerators. The basis for this shift is shown in Table I-43, whereby the estimated total per-unit cost including metal recycling and refrigerant recovery is negative $8.37 under the BAU (i.e., it is not a cost but net income) but the estimated total per-unit cost including metal recycling and refrigerant recovery is *positive* $9.07-$34.64 for Scenarios 1-3. Not only would this be a shift from a commodity to a service model but it could have unknown and possibly significantly adverse effects on the recycling of appliances based on the implications of imposing a net cost on the proper disposal of appliances rather than a profit.

One major uncertainty is the effect of charging for the recycling of appliances on the AB 1760 Metallic Discards Act. Charging for recycling of appliances may release landfills from the prohibition on accepting appliances for disposal insofar as the applicable “major appliances” may no longer contain enough metal to be economically feasible to salvage given the additional cost burden associated with foam recovery. This would depend on the approach and specific cost model used to implement an appliance foam recovery program.

I.10.2. New Technologies at Auto Shredders and for Recovering Foam Expansion Agents

According to the Institute of Scrap Recycling Industries Inc. (ISRI), new technologies could be implemented at auto shredders, landfills, and at fully automated appliance dismantling facilities to further minimize blowing agent emissions and transport demands. For example, Regenerative Thermal Oxidizers (RTOs), which are currently being piloted at one landfill in California, may be used at auto shredders to minimize emissions during appliance shredding. In addition, landfills could use shredder coating to minimize emissions of blowing agent from the shredded foam when it is used as landfill cover. This could help reduce emissions, particularly during compaction at landfills. There is no data however on either the benefits, effectiveness, or costs associated with any of this technology with respect to reduction of blowing agent emissions insofar as the technology was developed for other purposes.

In addition, various other technologies are emerging or under development for handling blowing agent, which could significantly reduce transport emissions and/or costs associated with automated foam recovery in future. For example, one technology (US Patent 4976862) can degas foam and create a byproduct powder and chemical that can be used in rubber manufacture.[45] This process, if approved by UNEP’s Technology and Economic Assessment Panel (TEAP), would eliminate the need for blowing agent transport to destruction/reclamation facilities (assumed in Scenario 3 of this analysis to be 750 miles away).

I.10.3. Potential Phase-down of HFCs in Insulating Foam

Since the early 1970s, insulating foam in appliances have contained blowing agents that are ODS and also have high-GWPs, although such substances have been gradually phased out per the Montreal Protocol (starting with the most potent ODS, CFCs, and then the HCFCs). HFCs, which do not deplete the stratospheric ozone layer, have since emerged as the leading foam blowing agents used in appliances sold in the United States. Although these gases tend to have

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[45] See <http://www.freepatentsonline.com/4976862.html> accessed June, 14, 2010.

lower GWPs than their CFC and HCFC predecessors, they are still high-GWP agents. Increasingly, more appliances are being manufactured each year with low-GWP blowing agents, such as hydrocarbons.

Although outside the scope of work of this particular research project, a national and international HFC production and import phase-down schedule may be a potentially cost-effective way to reduce GHG emissions from appliances during manufacture, use, and end-of-life. Presumably, the added cost (if any) of substitutes to HFC foam blowing agents would be passed on to the consumer at the time of appliance purchase. At the time of appliance recycling, if the substitute foam blowing agent was non-ODS, low-GWP, non- toxic and non-polluting,[46] the release of the blowing agent could be allowed as a normal air emission during the appliance recycling process. Therefore, no added cost would be borne by the appliance recycler to recover the foam blowing agent, unlike the management Scenarios 1, 2, and 3 in this research analysis.

A preliminary survey of existing studies to determine the cost-effectiveness of transitioning away from HFC to hydrocarbon foam blowing agents in appliances show extremely high one-time costs of up to $50 million per facility to retrofit appliance manufacturing facilities to use hydrocarbons (U.S. EPA 2006). The U.S. EPA analysis indicated that the added cost per appliance is about $20.90, based upon an added yearly cost of $11.2 million to produce 536,000 appliances per year. Adjusted for inflation the added cost per appliance in 2011 dollars is approximately $23 per appliance to use hydrocarbon foam blowing agents. With the average price of a new residential refrigerator/freezer at $900, the cost of transitioning to hydrocarbon foam agents adds 2.5% to the overall cost of an appliance.

However, despite the added cost of retrofitting appliance manufacturing facilities to use hydrocarbon foam expansion agents, it is estimated that more than 20% of the appliances currently sold in the United States contain hydrocarbon-based foam blowing agents. Presumably, as there is no regulation prohibiting the use of HFC foam blowing agents, the transition to hydrocarbon agents must be cost-effective enough to continue using the hydrocarbon agents.

Unsaturated HFCs, known as hydro-fluoroethers, or HFOs, present another low-GWP foam alternative to HFCs. The GWP of HFOs is 6, they are non-ODS, and are non-flammable. The insulating performance is greater than the currently used HFC-245fa and pentane hydrocarbon agents. HFO foam expansion agents are still in development and are not available commercially. Although cost and availability remain undetermined, HFOs may become viable alternatives to HFC or hydrocarbon foam expansion agents (DuPont 2009, 2010).

However, given the current widespread usage of HFC foam blowing agents and a 14-year average appliance lifetime, GHG reductions associated with an HFC phase-down in appliances would not be seen until 2025 - 2035 at the earliest, depending upon the schedule of the HFC phase-down.

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[46] The release of hydrocarbon refrigerants at disposal could lead to concerns regarding the release of volatile organic compounds (VOCs); while the venting of HCs from appliances at time of disposal is permitted in Europe, California and/or US regulators could prohibit it.

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I.12. Appendix A: Lessons Learned on Appliance Recycling from Other Countries

This appendix presents the experiences of Japan and the United Kingdom (UK) with regards to appliance recycling, as well as the lessons learned.

I.12.1. Japan

Japan's Home Appliance Recycling Law became effective in April 2001, and established comprehensive requirements and goals for recycling home appliances, including refrigerator-freezers. Initially, CFC recovery from insulation foam was not required, but this was made mandatory after approval of the March 2003 regulation "Fundamental Plan for Establishing a Material-Cycle Society" (Japan WMRD 2004).

The cost of comprehensive appliance recycling in Japan is largely borne by the consumer at the time of appliance disposal. According to the "Electric Appliance Recycling in Japan" fact sheet (Inform, 2003), the average cost at the time of disposal to the consumer is $30 to $38 per refrigerator-freezer, although the fact sheet notes this is not the full cost of recycling, with the following statement, "However, it is important to note that these fees are insufficient to cover all the costs of recycling and that manufacturers are responsible for the remaining costs." Therefore, it can be assumed that manufacturers internalize some recycling costs which are likely to be passed on to the consumer at the time of purchasing a new appliance. Indeed, in the translation of the "Law for Recycling of Specified Kinds of Home Appliances" written by the Japan Ministry of International Trade and Industry, the explanatory chart "The Home Appliance Recycling Law in Action" uses a refrigerator recycling fee of 4,830 yen, equivalent to $56.45 in US dollars.[47] The total cost to recycle an appliance includes not just the added cost of foam recovery, but also the cost of refrigerant recovery, compressor oil recycling, and any other materials found in the appliance with a negative value.

I.12.2. United Kingdom

On January 1, 2002, European Union environmental regulation 2037/2000 went into effect, which effectively mandated the recovery and management of all ODS from appliances, including refrigerants and insulating foam expansion agents (EU 2000). Because of the lack of appliance recycling infrastructure to recover foam, and the lack of funding to ensure the added recycling cost could be covered, most appliance recyclers stopped accepting appliances for recycling. Those that did accept the appliances stockpiled them into large piles that became known as "fridge mountains," which lasted for several years until it became profitable to once again recycle appliances (government-mandated subsidies were necessary for appliance recycling to proceed).

During the months that appliances were stockpiled, one of the major appliance recyclers in the UK went out of business, and several fridge mountain fires were reported. The appliance fires most likely resulted in the release of the refrigerant and the foam expansion agent from the appliances, which is the opposite of the intended GHG reductions promoted by the European Union ODS regulations (BBC 2004; BRASS 2002).

In a UK government inquiry into the cause of the collapse of appliance recycling in the UK after the new recycling regulations took effect, it was acknowledged that little attention was paid to the ability of existing recyclers to recover the greenhouse gases within the waste foam, and funding issues had apparently not been fully assessed prior to adopting regulation 2037/2000 (DEFRA 2002).

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[47] Based on an exchange rate of $1 (US) equivalent to 85.56 Japanese Yen on September 15, 2010.

Unintended Consequences of Regulating Foam Recovery from Appliances

It is not the intent of this lifecycle analysis to recommend any policy direction for appliance recycling. However, in the interest of providing a robust lifecycle analysis, it should be noted that mandating foam recovery and destruction from appliances could result in unintended consequences that could be both harmful to the recycling industry and the environment—if mandatory foam recovery from appliances is not accompanied by additional funding sources or additional facilities to process the foam. The following is a qualitative discussion of potential unintended consequences.

The United Kingdom “fridge mountain” issue discussed previously is an example of a series of problems that occurred as a result of requiring foam recovery from appliances without first ensuring adequate infrastructure and funding to accomplish appliance foam recovery.

In California, according to scrap metal shredders, an unintended consequence of mandating foam recovery from appliances, without first ensuring infrastructure and financial resources, would very likely be that appliances metals would no longer be recycled (ISRI, 2010). According to regulations promulgated as a result of the California Metallic Discards Act of 1991, “no solid waste facility shall accept for disposal any major appliance, vehicle, or other metallic discard which contains enough metal to be economically feasible to salvage as determined by the solid waste facility operator” (CIWMB 1993; PRC 1991). The converse side of this regulation is that if a metallic discard such as an appliance is *not* economically feasible to salvage (recycle), then landfilling the appliance is presumably allowable under California regulations. Under such a scenario, however, “leakage” of the end-of-life appliances may be more common than actual landfilling, with used appliances being sent to other states or countries that have no foam recovery requirements, as the value of the metal alone may make used appliances attractive for recycling. Alternatively, a scenario of non-compliance could result, where metal scrappers and recyclers accept appliance metals but without properly recovering/destroying the foam. In either case, because the greenhouse gases from the foam would still be unmanaged, there would be no benefit from any program that created a “perverse incentive” to ship used appliances out of California, to places where the environmental laws may be less stringent.

I.13. Appendix B: Detailed Cost and Emission Tables

I.13.1. Incremental Costs

Table I-51: Incremental Costs ($) by Scenario, Part A

Year	Transport Fuel Costs			Labor: Transport Costs			Labor: Foam Handling Costs		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
2010	—	779,128	864,814	—	3,807,161	4,042,309	13,258,437	13,258,437	2,284,856
2011	—	778,549	864,172	—	3,804,332	4,039,305	13,248,586	13,248,586	2,283,159
2012	—	860,176	954,775	—	4,203,193	4,462,802	14,637,619	14,637,619	2,522,534
2013	—	916,826	1,017,656	—	4,480,011	4,756,718	15,601,638	15,601,638	2,688,665
2014	—	924,600	1,026,284	—	4,517,998	4,797,051	15,733,927	15,733,927	2,711,463
2015	—	952,718	1,057,495	—	4,655,397	4,942,936	16,212,419	16,212,419	2,793,923
2016	—	974,869	1,082,082	—	4,763,635	5,057,859	16,589,357	16,589,357	2,858,881
2017	—	950,954	1,055,537	—	4,646,775	4,933,782	16,182,396	16,182,396	2,788,749
2018	—	969,920	1,076,588	—	4,739,450	5,032,180	16,505,133	16,505,133	2,844,367
2019	—	916,302	1,017,075	—	4,477,453	4,754,001	15,592,730	15,592,730	2,687,130
2020	—	899,588	998,522	—	4,395,778	4,667,282	15,308,298	15,308,298	2,638,113
2010–2020	—	9,923,630	11,015,000	—	48,491,181	51,486,225	168,870,540	168,870,540	29,101,840
2010–2020 NPV	—	7,802,641	8,660,751	—	38,127,101	40,482,010	132,777,630	132,777,630	22,881,868
2010–2050	—	20,566,248	22,828,059	—	100,495,645	106,702,729	349,976,082	349,976,082	60,312,166
2010–2050 NPV	—	12,323,132	13,678,392	—	60,216,192	63,935,427	209,702,887	209,702,887	36,138,570

Table I-52: Incremental Costs ($) by Scenario, Part B

Year	Energy Consumption Costs			Foam Disposal Fees			O&M Costs		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
2010	(5,497)	223,528	1,840,172	3,500,109	3,500,109	4,437,848	—	16,564,718	16,564,718
2011	(5,493)	223,362	1,838,804	3,497,509	3,497,509	4,416,035	—	16,552,410	16,552,410
2012	(6,068)	246,780	2,031,592	3,864,201	3,864,201	4,858,573	—	18,287,829	18,287,829
2013	(6,468)	263,033	2,165,390	4,118,693	4,118,693	5,156,751	—	19,492,248	19,492,248
2014	(6,523)	265,263	2,183,751	4,153,617	4,153,617	5,178,487	—	19,657,526	19,657,526
2015	(6,721)	273,330	2,250,162	4,279,934	4,279,934	5,291,692	—	20,255,340	20,255,340
2016	(6,877)	279,685	2,302,478	4,379,443	4,379,443	5,442,356	—	20,726,276	20,726,276
2017	(6,709)	272,824	2,245,995	4,272,008	4,272,008	5,395,995	—	20,217,830	20,217,830
2018	(6,843)	278,265	2,290,789	4,357,208	4,357,208	5,501,274	—	20,621,049	20,621,049
2019	(6,464)	262,882	2,164,154	4,116,342	4,116,342	5,194,725	—	19,481,118	19,481,118
2020	(6,346)	258,087	2,124,677	4,041,254	4,041,254	5,095,392	—	19,125,757	19,125,757
2010–2020	(70,009)	2,847,038	23,437,963	44,580,318	44,580,318	55,969,127	—	210,982,100	210,982,100
2010–2020 NPV	(55,046)	2,238,537	18,428,538	35,052,111	35,052,111	44,007,769	—	165,888,634	165,888,634
2010–2050	(145,091)	5,900,351	48,574,053	92,390,567	92,390,567	115,949,291	—	437,250,269	437,250,269
2010–2050 NPV	(86,937)	3,535,443	29,105,186	55,359,694	55,359,694	69,500,441	—	261,996,886	261,996,886

I.13.2. GHG Emissions Avoided

Table I-53: Annual Emissions Avoided for Each Scenario

Year	Direct Emissions: Foam Blowing Agent			Energy Consumption: Foam Handling			Transport		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
2010	165,022	165,022	227,607	38	(1,527)	(12,572)	—	(3,940)	(4,369)
2011	170,261	170,261	233,144	38	(1,526)	(12,562)	—	(3,937)	(4,366)
2012	194,035	194,035	263,893	41	(1,686)	(13,879)	—	(4,350)	(4,823)
2013	213,127	213,127	287,992	44	(1,797)	(14,793)	—	(4,636)	(5,141)
2014	221,300	221,300	297,212	45	(1,812)	(14,919)	—	(4,675)	(5,185)
2015	258,269	258,269	343,625	46	(1,867)	(15,373)	—	(4,818)	(5,342)
2016	286,924	286,924	384,856	47	(1,911)	(15,730)	—	(4,930)	(5,467)
2017	260,356	260,356	356,324	46	(1,864)	(15,344)	—	(4,809)	(5,332)
2018	268,107	268,107	366,716	47	(1,901)	(15,650)	—	(4,905)	(5,439)
2019	255,957	255,957	349,871	44	(1,796)	(14,785)	—	(4,633)	(5,138)
2020	256,296	256,296	349,918	43	(1,763)	(14,515)	—	(4,549)	(5,044)
2010–2020	2,549,655	2,549,655	3,461,157	478	(19,450)	(160,123)	—	(50,180)	(55,647)
2010–2050	5,911,499	5,911,499	8,024,090	991	(40,310)	(331,848)	—	(103,996)	(115,325)

I.13.3. Incremental Criteria Pollutant Emissions

Table I-54: Annual Incremental NO_x Emissions in Each Scenario (MT)

Year	Scenario 1			Scenario 2			Scenario 3		
	Non Point	Point	Total	Non Point	Point	Total	Non Point	Point	Total
2010	—	(0.1)	(0.1)	11.3	2.4	13.7	13.4	19.7	33.1
2015	—	(0.1)	(0.1)	13.9	2.9	16.8	16.4	24.0	40.5
2020	—	(0.1)	(0.1)	13.1	2.8	15.8	15.5	22.7	38.2
2025	—	(0.1)	(0.1)	11.0	2.3	13.3	13.0	19.0	32.0
2030	—	(0.0)	(0.0)	8.1	1.7	9.8	9.6	14.1	23.7
2035	—	(0.0)	(0.0)	5.1	1.1	6.2	6.1	8.9	14.9
2040	—	(0.0)	(0.0)	2.0	0.4	2.4	2.3	3.4	5.7
2045	—	—	—	—	—	—	—	—	—
2050	—	—	—	—	—	—	—	—	—
2010–2020	—	(0.7)	(0.7)	144.4	30.4	174.8	170.9	250.5	421.4
2010–2050	—	(1.6)	(1.6)	299.2	63.1	362.3	354.2	519.1	873.3

Table I-55: Annual Incremental PM10 Emissions in Each Scenario (MT)

Year	Scenario 1			Scenario 2			Scenario 3		
	Non Point	Point	Total	Non Point	Point	Total	Non Point	Point	Total
2010	—	(0.1)	(0.1)	0.3	2.1	2.4	0.4	17.1	17.5
2015	—	(0.1)	(0.1)	0.4	2.5	2.9	0.5	21.0	21.4
2020	—	(0.1)	(0.1)	0.4	2.4	2.8	0.4	19.8	20.2
2025	—	(0.0)	(0.0)	0.3	2.0	2.3	0.4	16.6	16.9
2030	—	(0.0)	(0.0)	0.2	1.5	1.7	0.3	12.3	12.5
2035	—	(0.0)	(0.0)	0.1	0.9	1.1	0.2	7.7	7.9
2040	—	(0.0)	(0.0)	0.1	0.4	0.4	0.1	3.0	3.0
2045	—	—	—	—	—	—	—	—	—
2050	—	—	—	—	—	—	—	—	—
2010–2020	—	(0.7)	(0.7)	4.0	26.5	30.5	4.7	218.3	223.0
2010–2050	—	(1)	(1)	8	55	63	10	452	462

Table I-56: Annual Incremental PM2.5 Emissions in Each Scenario (MT)

Year	Scenario 1			Scenario 2			Scenario 3		
	Non Point	Point	Total	Non Point	Point	Total	Non Point	Point	Total
2010	—	(0.0)	(0.0)	0.1	0.6	0.6	0.1	4.6	4.6
2015	—	(0.0)	(0.0)	0.1	0.7	0.7	0.1	5.6	5.7
2020	—	(0.0)	(0.0)	0.1	0.6	0.7	0.1	5.3	5.4
2025	—	(0.0)	(0.0)	0.1	0.5	0.6	0.1	4.4	4.5
2030	—	(0.0)	(0.0)	0.0	0.4	0.4	0.0	3.3	3.3
2035	—	(0.0)	(0.0)	0.0	0.3	0.3	0.0	2.1	2.1
2040	—	(0.0)	(0.0)	0.0	0.1	0.1	0.0	0.8	0.8
2045	—	—	—	—	—	—	—	—	—
2050	—	—	—	—	—	—	—	—	—
2010–2020	—	(0.2)	(0.2)	0.7	7.1	7.8	0.9	58.2	59.1
2010–2050	—	(0)	(0)	2	15	16	2	121	122

Table I-57: Annual Incremental SO_x Emissions in Each Scenario (MT)

Year	Scenario 1			Scenario 2			Scenario 3		
	Non Point	Point	Total	Non Point	Point	Total	Non Point	Point	Total
2010	—	(0.1)	(0.1)	0.3	5.3	5.6	0.3	43.5	43.9
2015	—	(0.2)	(0.2)	0.4	6.5	6.8	0.4	53.2	53.7
2020	—	(0.2)	(0.2)	0.3	6.1	6.4	0.4	50.3	50.7
2025	—	(0.1)	(0.1)	0.3	5.1	5.4	0.3	42.1	42.4
2030	—	(0.1)	(0.1)	0.2	3.8	4.0	0.2	31.1	31.4
2035	—	(0.1)	(0.1)	0.1	2.4	2.5	0.2	19.6	19.8
2040	—	(0.0)	(0.0)	0.1	0.9	1.0	0.1	7.6	7.6
2045	—	—	—	—	—	—	—	—	—
2050	—	—	—	—	—	—	—	—	—
2010–2020	—	(1.7)	(1.7)	3.7	67.4	71.0	4.4	554.5	558.8
2010–2050	—	(3)	(3)	8	140	147	9	1,149	1,158

I.14. Appendix C: Foam GHG Losses during Recycling and Landfilling—Assumptions and Uncertainties

This appendix presents a complete discussion of foam GHG losses during the appliance recycling process and afterwards when the waste foam has been landfilled.

I.14.1. Foam GHG Losses in Landfills

Typically, foam GHG losses of 1% - 68% occur when the foam is shredded in an auto shredder during the metal separation process, with a weighted average loss of 24%. Further foam GHG losses (estimated at 19%) occur when the shredded foam is placed in a landfill (e.g., during initial compaction and initial releases before biological attenuation or landfill gas capture systems are in place) (Fredenslund, et al. 2005). For HCFC-based blowing agents, after the foam is landfilled, another 2% of the foam GHG is estimated to eventually be released due to incomplete biological attenuation or landfill gas capture and combustion; therefore, it is estimated that up to 45% of HCFC foam GHG is emitted into the atmosphere from appliance shredding, with the remaining 55% assumed to be biologically attenuated to low-GWP breakdown products, or captured and combusted within the landfill gas collection system (CAR 2010). However, the extent to which biological attenuation or landfill gas capture/combustion will reduce GHG foam emissions in the landfill depends on the type of blowing agent, as well as a number of other factors (e.g., landfill conditions). For example, 100% of HFC-134a blowing agent is released once in the landfill.

Although up to more than 50% of the appliance foam GHG may be mitigated naturally through existing business-as-usual disposal practices of shredded foam for some blowing agent types, even greater emission reductions—of up to 85% - 95%—can be achieved through foam recovery and destruction (incineration).

Uncertainties of Foam GHG Loss Assumptions

The previously stated foam GHG loss assumptions are based on the best available data from limited studies and modeling assumptions, and are not based upon actual field measurements of high-GWP emissions from landfills. The following discusses the data uncertainties regarding foam GHG losses from recycling and landfilling.

Emissions from Appliance Shredding

The estimated 24% loss of foam GHG from appliance shredding is based upon a 2005 study covering three appliance recycling facilities in Tennessee, conducted by W.Z. Baumgartner & Associates, with further analysis by the Technical University of Denmark (Fredenslund, et al. 2005). No California-specific studies have been conducted concerning appliance foam GHG losses. The recycling facilities in Tennessee produced shredded appliance foam that varied greatly in terms of GHG loss due to shredding, from a 1% loss up to a 68% loss, with a weight-averaged loss of 24%. Generally, the smaller the shredded foam particle, the greater the loss of the embedded foam GHG expansion agent. The study results are shown below:

Table I-58: Particle size distribution and release of foam blowing agent (BA) from shredding.

Shredder Facility/ Foam Particle Size	Adjusted Size Distribution (%w)	Release of BA (%) from Shredding	Weighted Average BA Release (%)
Harriman, dry shredding mode			
>32 mm	54	27	
16–32 mm	40	41	34
8–16 mm	4	39	
< 8 mm	2	68	
Harriman, wet shredding mode			
>32 mm	52	12	
16–32 mm	39	16	17
8–16 mm	8	39	
< 8 mm	2	61	
Nashville			
>32 mm	34	1	
16–32 mm	47	9	9
8–16 mm	13	7	
< 8 mm	5	57	
Pulaski			
>32 mm	15	24	
16–32 mm	69	40	38
8–16 mm	14	42	
< 8 mm	2	57	
Average			
>32 mm	39	16	
16–32 mm	49	26	24
8–16 mm	10	32	
< 8 mm	3	61	

The wide range of emissions from shredded foam, from 1% to 68% loss of foam blowing agent, suggests that the average 24% loss rate may over- or under- estimate actual emissions from a given recycling facility. (Note also that the shredding losses estimated at 24% are somewhat comparable to the 15% of losses estimated from manual foam removal.)

Additionally, the study does not take into account technological advances since 2005 and the stricter environmental controls in place for metal shredding facilities in California. For example, one state-of-the-art metal recycling facility in California is piloting a regenerative thermal oxidation (RTO) system to reduce emissions of volatile organic compounds, greenhouse gases, and other shredder emissions by up to 99% (SA Recycling 2011b). Although the capture efficiency of this facility appears to be a promising technology for reducing appliance GHG emissions, it is not current “business as usual” recycling technology. The 24% loss rate remains the best available estimate from California shredding facilities.

Short-term Emissions from Landfilled Foam

The estimated 19% release of GHG from recently landfilled foam through compaction loss (11%), and release during the microbially inactive period (8%) is not based upon any actual landfill measurements. Rather, this estimate is based upon the best engineering judgment of the research team (Fredenslund, et al. 2005). Therefore, it is possible that the 19% loss assumption over-estimates actual foam GHG losses. However, pending better data, the 19% loss assumption will be used in this particular analysis.

Long-term Emissions from Landfilled Foam

After foam has been landfilled and is placed in a covered waste cell with anaerobic conditions and a landfill gas collection system, additional GHG losses from landfilled foam vary by blowing agent type; for HCFC blowing agents, losses are estimated to be as low as 2% of the foam GHG content at EOL, whereas for HFC-134a blowing agent, eventual losses in landfills are estimated to be 100% (which is equivalent to 57% of what remained at EOL). These estimates are based upon studies researching biological degradation of foam (Scheutz et al. 2007 and 2007b) and upon studies of landfill gas capture and control (SWICS 2007, 2008; Environment Canada 1999, 2000a, 2000b, 2000c, 2002, 2005.)

Combustion

More than 95% of waste in California is within landfills that have methane collection and combustion systems (ARB. 2009c). It is estimated that the operating temperatures in typical U.S. landfill gas combustion systems (boiler, turbine, reciprocating engine, or flare), operate between 1100 and 1150°F (U.S. EPA 2008). Due to strict methane emission control systems required in California landfills, industry experts estimate that California landfill gas control systems operate at about 1400°F, which is the required temperature for new landfills operating in the South Coast (White 2008). Assuming that landfill gas combustion systems operate at the lower end of the combustion range of 1100°F, this temperature is sufficient to reduce HCFC-141b and HFC-245fa foam agents, which have auto-destruction temperatures of 1022°F and 482°F, respectively. HFC-134a foam expansion agent, with an auto-destruction temperature of 1369°F, is assumed to undergo no reduction in landfill combustion systems, but will be emitted. Currently, 3% of disposed appliances contain HFC-134a foam blowing agent; this percent will increase to 7% in 2015, before phasing out completely by 2017 (HFC-134a foam agent was phased out of manufacturing in 2002).

Biological Attenuation

Up to 60% of HCFC-141b foam blowing agent is estimated to attenuate in landfills due to microbial activity, which converts the HCFC to HFCs. However, as the foam release rate for HCFC-141b is faster than the attenuation rate, in this analysis it is assumed that HCFC-141b is not biologically attenuated in landfills, but is released from the foam and collected within the landfill gas collection and combustion system. HFCs are not attenuated by biological degradation, as the carbon-fluorine bond is apparently too strong for microbes to break (Scheutz, et al. 2007b).

I.14.2. Summary

Given the landfill assumptions described above, this analysis estimates that between 45% and 100% of the GHG within appliance insulating foam is emitted from appliance recycling and subsequent landfilling of the shredder fluff (24% loss at shredding, 19% loss during initial landfilling, and 2% to 57% loss during long-term landfilling, depending on the blowing agent). Although it is beyond the scope of this research to verify losses of foam due to landfill compaction, due to uncertainties involving best estimates of compaction losses, actual foam emissions may be as low as 26% of the appliance foam GHG content for HCFC-141b blowing agent (24% loss at shredding and 2% due to long-term landfilling).

I.15. Appendix D: Stakeholder Comments to Draft Version of LCA

Six stakeholders submitted 72 separate comments on earlier draft versions of the LCA on household refrigerators and freezers reaching end of life. Subsequently, several meetings between ICF researchers, CARB staff, and stakeholders took place to clarify stakeholder comments and concerns with the draft LCA, and also to clarify the purpose, scope of work, and limitations of the LCA research.

The following list summarizes the comments, with similar comments grouped together. All comments have been addressed in the revised LCA, with the resulting response/action summarized after each comment category. Almost all comments were directly incorporated into the LCA input assumptions, and the results were refined as a result of the stakeholder comments. A few comments addressed issues that were not within the scope of work for this particular LCA project. For these comments, they were addressed in a qualitative manner (non-quantitative), with an accompanying discussion that did not change emissions or cost results. These comments are noted in the summary titled “Comments Resulting in Qualitative Discussion.”

I.15.1. Comments Summary:

1. Comment: The LCA significantly underestimates the cost of appliance recycling with comprehensive foam GHG recovery and management.

Response/Action: Additional research was undertaken to ascertain the total cost involved with foam GHG recovery and management, looking at both automated and manual foam recovery. The cost estimates were revised accordingly, which has been reflected throughout the revised LCA.

2. Comment: The LCA significantly overestimates the business-as-usual cost of appliance recycling (no foam GHG recovery).

Response/Action: Working closely with metal shredder stakeholders, more accurate cost information was used to reflect a lower business-as-usual cost of recycling appliances.

3. Comment: The LCA significantly overestimates GHG emissions from landfilled waste foam generated by recycled appliances.

Response/Action: Emissions from landfilled foam were conservatively revised downward, noting that biological attenuation, sorption, and combustion of landfill gas potentially reduces landfill gas. However, it should be noted that these emission reductions are somewhat speculative, as they assume that landfills emit few GHGs from landfilled foam. Additional research is recommended to measure the GHG impact of specific foam expansion agents emitted from landfilled foam.

I.15.2. Comments Resulting in Qualitative Discussion:

1. Comment: The LCA significantly overestimates GHG emissions occurring at the time of appliance shredding and initial landfilling.

Response/Action: Based upon the best available study of appliance GHGs emitted at the time of shredding/recycling (Scheutz, et al. 2007), researchers determined that typical foam GHG losses at the time of appliance shredding range from 1% to 68%, with a weighted average of

24%. Although the 2007 research was conducted in Tennessee at three separate recycling facilities, the research appeared to be valid and relevant to appliance recycling GHG emissions in California. Additional foam GHG losses of 19% were estimated to occur within a few weeks after shredded foam has been landfilled (Fredenslund, et al., 2005). These additional losses of 19% are based on best engineering estimates and not actual foam GHG measurements. It is possible that the additional post-shredding losses overestimate emissions. However, because shredded foam is typically used as an Alternative Daily Cover (ADC) in California landfills, it is also likely that the recently shredded foam continues to emit GHGs from the insulation pore spaces newly exposed. It was not within the scope of work of this LCA to undertake separate foam emission studies at shredding facilities or landfills. Furthermore, the very conservative (low) emissions estimate assumptions from landfilled foam served to balance any likely over-estimate from the 19% emissions estimate. Additional discussion of the issue is included in this LCA in section 1.2, “Background,” and section 1.14 “Appendix C: Foam GHG Losses during Recycling and Landfilling – Assumptions and Uncertainties”.

2. Comment: The diesel fuel cost of $2.54/gallon underestimates the current fuel cost and therefore, the transportation costs are underestimated.

Response/Action: The diesel fuel cost of $2.54/gallon was accurate as of July 2009, when the transportation component of the LCA was calculated. As of September 2011, diesel fuel costs in California were approximately $4.00/gallon. Although fuel cost has increased 57% between 2009 and 2011; this increase adds approximately 1% to the overall cost of recycling appliances with foam recovery, as the transportation costs are a minor fraction of overall costs compared to labor, equipment purchase and maintenance, etc. Within the scope of the work, it was not feasible to re-calculate all transportation costs.

3. Comment: The LCA does not take into account serious “unintended consequences” of any mandatory foam recovery management scenario, which may include the majority of appliance recycling to leave California, more appliances being landfilled, and increased appliance illegal dumping by residents not willing to pay for increased recycling costs.

Response/Action: Potential unintended consequences are an important concern, and are discussed in a new LCA section 1.10.1, “Unintended Consequences of Regulating Foam Recovery from Appliances.” Additionally, some unintended consequences are also discussed in the new section 1.12. “Appendix A: Lessons Learned on Appliance Recycling from Other Countries.”

I.16. Appendix E: Report Figures presented as Data

The following tables show the data which ICF used to develop the figures and graphs presented in Part I. LCA on Household Refrigerators and Freezers Reaching End-of-Life of this analysis. In each case, numbered tables are followed by a figure reference in brackets (e.g., from Figure I-xx), and the title of the relevant figure as it is shown in the body of the report.

Table I-59 (from Figure I-5): Potential Climate Impact of Blowing Agent Reaching EOL (MMTCO$_2$eq), 2010-2050

Year	Total Banks of Blowing Agent at EOL
2010	0.6
2011	0.6
2012	0.7
2013	0.7
2014	0.8
2015	0.8
2016	1.0
2017	1.0
2018	1.0
2019	0.9
2020	0.9
2021	0.9
2022	0.9
2023	0.9
2024	0.9
2025	0.8
2026	0.8
2027	0.7
2028	0.7
2029	0.7
2030	0.7
2031	0.6
2032	0.6
2033	0.5
2034	0.5
2035	0.4
2036	0.4
2037	0.3
2038	0.3
2039	0.2
2040	0.2
2041	0.1
2042	0.1
2043	—
2044	—
2045	—
2046	—
2047	—
2048	—
2049	—
2050	—

Table I-60 (from Figure I-8): ODP-Weighted Emissions Avoided (MT ODP), 2010-2030

Year	Scenario 1 / Scenario 2	Scenario 3
2010	23.76	33.29
2011	23.50	32.93
2012	25.70	36.01
2013	27.10	37.98
2014	27.05	37.90
2015	22.24	31.16
2016	14.22	19.93
2017	13.36	18.72
2018	13.05	18.28
2019	11.72	16.43
2020	10.38	14.55
2021	8.57	12.01
2022	7.45	10.44
2023	6.32	8.86
2024	5.18	7.26
2025	5.21	7.29
2026	5.23	7.33
2027	5.26	7.37
2028	5.28	7.40
2029	—	—
2030	—	—

Table I-61 (from Figure I-8): Cumulative Net GHG Emissions Avoided (MMTCO$_2$eq), 2010-2050

Year	Total Emissions		
	Scenario 1	Scenario 2	Scenario 3
2010	0.17	0.16	0.21
2011	0.34	0.32	0.43
2012	0.53	0.51	0.67
2013	0.74	0.72	0.94
2014	0.96	0.93	1.22
2015	1.22	1.19	1.54
2016	1.51	1.47	1.90
2017	1.77	1.72	2.24
2018	2.04	1.98	2.59
2019	2.29	2.23	2.92
2020	2.55	2.48	3.25
2021	2.79	2.72	3.56
2022	3.04	2.96	3.88
2023	3.29	3.20	4.20
2024	3.53	3.44	4.51
2025	3.76	3.66	4.81
2026	3.98	3.88	5.09
2027	4.18	4.07	5.35
2028	4.37	4.26	5.60
2029	4.57	4.46	5.85
2030	4.76	4.64	6.09
2031	4.94	4.81	6.32
2032	5.10	4.97	6.52
2033	5.24	5.11	6.71
2034	5.37	5.24	6.88
2035	5.49	5.36	7.04
2036	5.60	5.46	7.17
2037	5.69	5.55	7.29
2038	5.76	5.62	7.38
2039	5.82	5.68	7.46
2040	5.87	5.72	7.52
2041	5.90	5.75	7.56
2042	5.91	5.77	7.58
2043	5.91	5.77	7.58
2044	5.91	5.77	7.58
2045	5.91	5.77	7.58
2046	5.91	5.77	7.58
2047	5.91	5.77	7.58
2048	5.91	5.77	7.58
2049	5.91	5.77	7.58
2050	5.91	5.77	7.58

Table I-62 (from Figure I-9): Total Annual GHG Emissions Avoided ($MTCO_2eq$), 2010-2050

Year	Total Emissions Avoided ($MTCO_2eq$)		
	Scenario 1	Scenario 2	Scenario 3
2010	165,060	159,556	210,666
2011	170,298	164,798	216,216
2012	194,076	187,999	245,190
2013	213,171	206,694	268,058
2014	221,345	214,813	277,108
2015	258,315	251,584	322,910
2016	286,971	280,084	363,659
2017	260,401	253,683	335,647
2018	268,154	261,302	345,627
2019	256,001	249,528	329,948
2020	256,340	249,984	330,358
2021	242,720	236,820	312,781
2022	246,492	240,616	317,617
2023	250,295	244,445	322,494
2024	242,766	237,181	312,774
2025	229,924	224,606	296,234
2026	216,946	211,899	279,520
2027	203,834	199,059	262,632
2028	190,584	186,086	245,568
2029	200,757	196,538	258,567
2030	187,350	183,412	241,299
2031	173,803	170,150	223,851
2032	160,116	156,751	206,223
2033	146,288	143,213	188,413
2034	132,317	129,536	170,419
2035	118,203	115,719	152,241
2036	103,945	101,760	133,877
2037	89,541	87,659	115,326
2038	74,991	73,415	96,585
2039	60,293	59,025	77,654
2040	45,446	44,490	58,532
2041	30,449	29,809	39,216
2042	15,300	14,979	19,706
2043	—	—	—
2044	—	—	—
2045	—	—	—
2046	—	—	—
2047	—	—	—
2048	—	—	—
2049	—	—	—
2050	—	—	—

Table I-63 (from Figure I-11): Total Incremental Criteria Pollutant Emissions, 2010-2050 (MT)

	Scenario 1	Scenario 2	Scenario 3
NOx	(1.6)	362.3	873.3
PM10	(1.4)	63.2	462.2
PM2.5	(0.4)	16.2	122.4
SOx	(3.4)	147.2	1,158.2

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II. LCA on Other Stationary Refrigeration/Air-Conditioning Equipment Reaching End-of-Life

II.1. Background

Refrigerant emissions are significant contributors to overall greenhouse gas (GHG) emissions in California, with estimated emissions for baseline year 2010 of 24.3 million pounds of refrigerant, with a climate impact of 23 million metric tons of carbon dioxide equivalent ($MMTCO_2eq$). For comparison, the total GHG emission goal in California in 2020 is 427 $MMTCO_2eq$ or less.

Due to the phase-out of high-GWP chlorofluorocarbons (CFCs), such as CFC-12 (GWP of 8,100), greenhouse gas emissions from refrigerants have not risen as dramatically as projected several decades ago. Relatively lower-GWP replacements, including hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) still have GWPs between 1,500 and 3,300.

The California Air Resources Board (ARB) approved a Stationary Equipment Refrigerant Management Program proposed rule (RMP rule) in December 2009, with final approval by the State Office of Administrative Law in October 2010. The rule covers commercial refrigeration systems using a refrigerant with a global warming potential (GWP) of 150 or greater, with a refrigerant charge in at least one system containing more than 50 pounds of refrigerant. Commercial air-conditioning used for comfort cooling, with a refrigerant charge greater than 50 pounds of refrigerant, is covered by maintenance and inspection rules, but are exempt from registration and reporting requirements. (Note that in this section of the LCA, “large” refrigeration/AC units refers to refrigeration/AC systems or equipment with more than 50 lbs of refrigerant in an individual system; “small” refers to refrigeration/AC equipment or systems with 50 lbs or less refrigerant in an individual system.) Residential refrigeration and air-conditioning is not directly addressed by the rule, but fall into servicing practice requirements of the rule.

The ARB Refrigerant Management Rule is projected to significantly decrease refrigerant emissions from large commercial refrigeration equipment by 2020. ARB regulations covering commercial refrigeration and AC systems will be phased in from 2012 through 2016. It is expected that anticipated refrigerant emission reductions will be fully realized by 2020. Specifically, due to the RMP Rule, annual emissions from refrigeration/AC systems (containing more than 50 lbs of refrigerant) are projected to decrease from 15.9 to 8.1 $MMTCO_2eq$, or about half of BAU emissions. Figure II-1 presents the relative emissions by refrigeration/AC sector in 2020, and Figure II-2 presents BAU refrigerant emissions of ODS and HFC refrigerants (expressed in $MMTCO_2eq$) in California from 2010 through 2050 (which includes RMP Rule expected reductions). Note that 1 $MMTCO_2eq$ is approximately equal to 1 million pounds of refrigerant emissions for the current mix of high-GWP refrigerants used in California.

Figure II-1: Projected BAU Emissions from the Refrigeration/AC Sector in 2020
Following Implementation of ARB's Refrigerant Management Rule

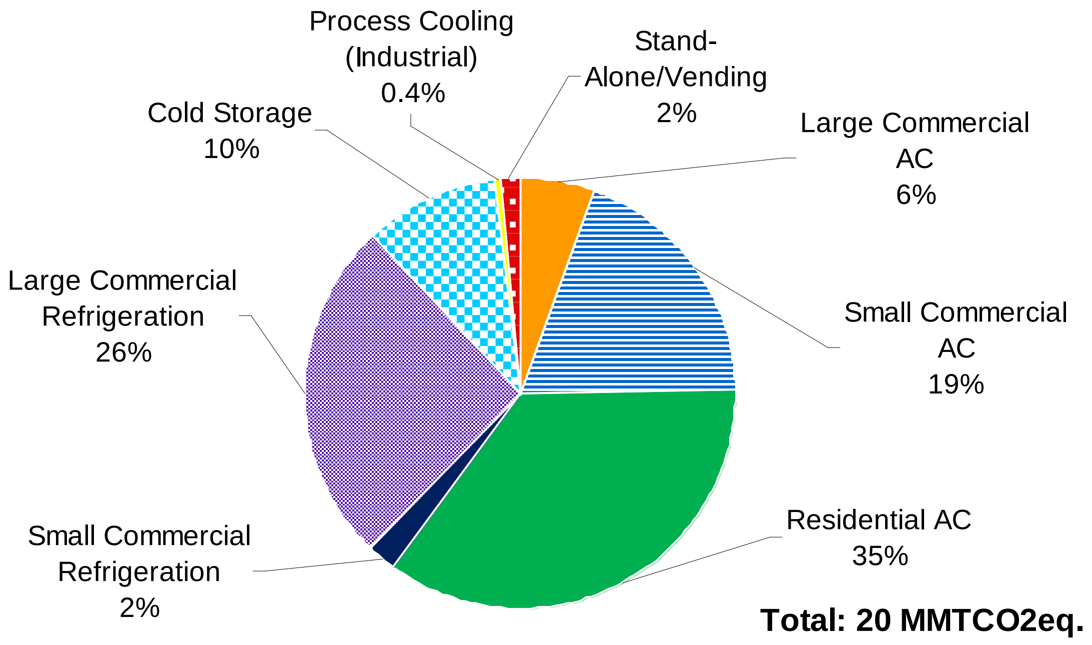
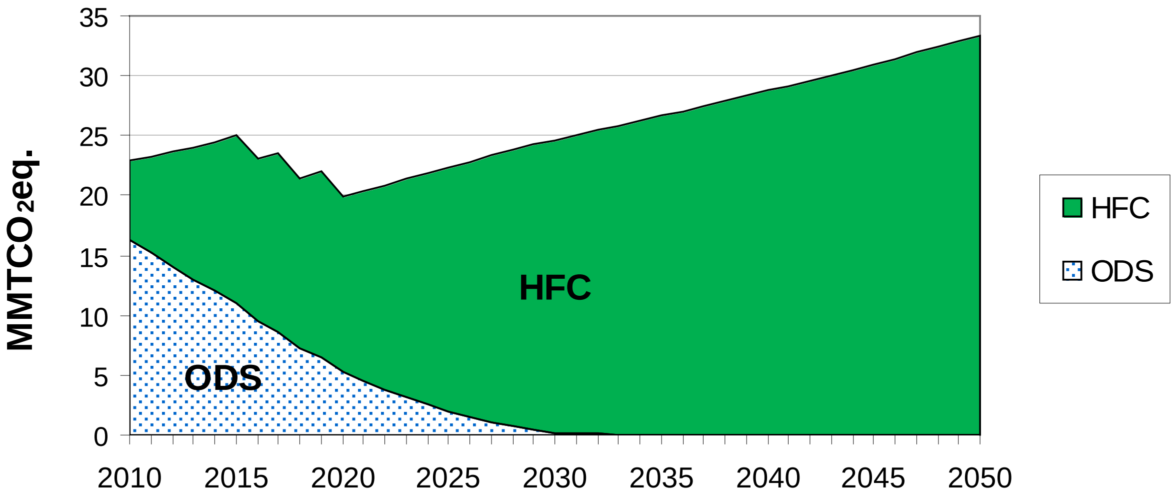


Figure II-2: Total BAU Projected Emissions of ODS and HFC Refrigerants
Following Implementation of ARB's Refrigerant Management Rule



Although the projected emission reductions associated with the RMP Rule are significant, emissions from the refrigeration/AC sector are expected to eventually exceed current (pre-RMP Rule) baseline levels, due to economic and population growth. Moreover, while the Refrigerant Management Rule aims to minimize refrigerant emissions during the operation of refrigeration/AC equipment, it does not directly address emissions that may occur at equipment disposal or end-of-life (EOL).

Currently, federal regulations mandate refrigerant recovery at equipment EOL, but the levels of compliance with such regulations are unknown and difficult to assess. Stronger enforcement and compliance (e.g., additional reporting requirements), economic incentives, or other means can be used to augment compliance with EOL refrigerant recovery regulations. In particular, some regulatory or non-regulatory policy options that could be used to increase compliance, described further in Section II.5 include:

- Tradable credit/certificate system;
- Taxes on virgin refrigerant sales and rebates on the return of used refrigerants for destruction; and/or
- Producer responsibility schemes.

In 2010, it is estimated that over 1,092,000 units of equipment will reach EOL, potentially containing up to 10.8 million pounds of refrigerant (assuming a full refrigerant charge at time of disposal). Thus, significant emissions can be avoided if full refrigerant recovery occurs at equipment disposal. However, actual emissions avoidable through refrigerant recovery at equipment EOL are dependent on the quantity of refrigerant remaining in the system at EOL, the efficiency of recovery equipment, and the extent to which recovery is practiced among technicians.

The quantity of refrigerant remaining in systems at EOL and the efficiency of recovery equipment was recently estimated by ICF in a study prepared for the European Commission. As summarized below, the study found that between 54% and 81% of the original refrigerant charge is potentially recoverable from refrigeration/AC equipment at EOL.

Table II-1: Estimated Refrigerant Recovery Potential from Refrigeration/AC Equipment at EOL in the European Union

Sub Sector	End Use	Refrigerant Remaining at EOL		Refrigerant Technically Recoverable at EOL	Total Potentially Recovered at EOL	
		EU 15	EU 12		EU 15	EU 12
Refrigeration	Small Commercial	90%	80%	90%	81%	72%
	Medium/ Large Commercial	70%	60%	95%	67%	57%
	Refrigerated Transport—Land	70%[e]	60%	90%	63%	54%
	Refrigerated Transport—Ships	60%	50%	95%	57%	48%
	Industrial Refrigeration	60%	50%	95%	57%	48%
Stationary AC	Small Stationary	90%	80%	90%	81%	72%
	Large Stationary (Chillers)	80%	70%	95%	76%	67%

Source: ICF (2010a).

The extent to which recovery is practiced among technicians is the other critical factor in estimating actual recovery levels in California. The rate of refrigerant recovery could change over time, as technician knowledge and capacity increase, enforcement becomes stronger, and/or economic incentives expand.

Based on anecdotal information, it is likely that recovery rates from larger equipment are higher. According to a recent study by Barrault and Clodic (2008), there are no economic drivers that create an incentive to improve the recovery of refrigerant from small equipment (e.g., domestic refrigerators, small AC units, MVACs), since the costs of recovery equipment (about $3,500 for an MVAC recovery device) and labor (roughly 15 minutes required) outweigh the economic gains that can be reaped by recovering a few pounds of refrigerant worth only several dollars per pound. In addition, because small equipment is often transported to a recycling plant prior to refrigerant recovery, refrigerant losses during transport/handling are common. As a result, it is estimated that 2% or less of refrigerant is recovered from small equipment at EOL, whereas 70%-80% of refrigerant is recovered from large equipment (Barrault and Clodic 2008). For this reason, large equipment manufacturers and service providers are likely to exhibit high levels of recovery, as are those dealing with very large equipment types (e.g., industrial refrigeration systems, chillers). This is especially true in areas that have a long history of rigorous technician training/certification programs (ICF 2008c). At EOL, large commercial refrigerated equipment is typically handled by installation companies that recover refrigerant for reuse, reclamation, or destruction, and then decommission the equipment for recycling.

Refrigerant Recycling versus Reclamation

Recycling and reclamation of refrigerant are defined under 40 CFR 82.152 as:

Recycling: To extract refrigerant from an appliance and clean refrigerant for reuse without meeting all of the requirements for reclamation. In general, recycled refrigerant is refrigerant that is cleaned using oil separation and single or multiple passes through devices, such as replaceable core filter-driers, which reduce moisture, acidity, and particulate matter. These procedures are usually implemented at the field job site.

Note that under section 608, refrigerant recovered and/or recycled can be returned to the same system or other systems owned by the same person without restriction; however, if the refrigerant changes ownership, it must be reclaimed. Under section 609, refrigerant can be removed from one car's air conditioner, recycled on site, and then charged into a different car.

Reclamation: to reprocess refrigerant to all of the specifications in appendix A to 40 CFR part 82, subpart F (based on ARI Standard 700-1995, Specification for Fluorocarbons and Other Refrigerants) that are applicable to that refrigerant and to verify that the refrigerant meets these specifications using the analytical methodology prescribed in section 5 of appendix A of 40 CFR part 82, subpart F.

Reclamation requires specialized machinery not available at a particular job site or auto repair shop. The technician will recover the refrigerant and then send it either to a general reclaimer or back to the refrigerant manufacturer.

Once refrigerant is recovered and collected and consolidated, it can be stored indefinitely or sent for destruction, recycling, or reclamation (see text box “Refrigerant Recycling versus Reclamation,” above). The decision on the fate of the refrigerant is based on several considerations, including the cost of each option and the demand for reclaimed or recycled refrigerant (e.g., for servicing existing equipment). Informational, financial, technological, logistical, and legal barriers may stand in the way of effective recovery and subsequent reclamation or destruction.

II.2. Purpose

This section of the analysis assesses potential emission reductions and costs associated with the recovery and subsequent reclamation or destruction of refrigerant from stationary equipment at EOL, to better understand the magnitude of emissions avoidable at EOL by equipment type. Specifically, this section addresses refrigerant recovery at EOL from commercial refrigeration systems covered by the RMP rule, as well as smaller (< 50 lbs) commercial refrigeration systems; and all sizes of commercial air-conditioning, residential air-conditioning, standalone refrigeration units, and vending machines. These equipment types are defined in Table II-2. Note that this analysis does not address residential refrigerators/freezers, as this sector is analyzed in its own separate section of this LCA. It also does not address mobile AC or refrigeration systems.

Table II-2: Refrigeration/AC Equipment Types Addressed in this Assessment

Refrigeration or AC Equipment Category	Defining characteristics	Included in RMP Rule Emissions and Cost ISOR Analysis?
Small Commercial AC	All AC systems used for commercial purposes, 50 lbs or less refrigerant charge.	No
Residential AC	Residential AC systems.	No
Centralized Systems	Large (200 lbs or more refrigerant charge) refrigeration systems used primarily in the retail food sector.	Yes
Chillers	Includes systems with 200 lbs or more refrigerant charge used for AC in commercial facilities.	Yes
Cold Storage	Includes all types of cooling systems used for refrigerated warehouses and cold storage facilities.	Yes
Condensing Units	Refrigeration condensing units between 50 and 200 lbs refrigerant charge, used in commercial refrigeration (primarily retail food).	Yes
Process Cooling (industrial)	Also known as industrial process cooling, includes all very large (2,000 lbs or more refrigerant charge) systems used in food and drink processing, and chemical and other manufacturing.	Yes
Small Commercial Refrigeration	All refrigeration systems used for commercial purposes, 50 lbs or less refrigerant charge.	No
Stand-Alone Units	Stand-alone cases used in retail food.	No
Unitary AC	AC systems used for commercial purposes, between 50 and 200 lbs refrigerant charge.	No
Vending Machines	Refrigerated vending machines.	No

Due to the uncertainty associated with actual refrigerant recovery levels from equipment at EOL in California, this analysis reviews the potential emissions avoidable and costs associated with three recovery scenarios: 10%, 50%, and 90% of the original equipment charge.

II.3. Key Assumptions

This section outlines the key basic assumptions, those specific to estimating emissions, and those specific to estimating costs. For each of the three scenarios, the following emission impacts are evaluated:

- Avoided direct ODS and GHG emissions due to the recovery and destruction/reclamation of refrigerant;
- Indirect CO_2 and criteria air pollutant emissions associated with the energy consumed during the destruction and reclamation processes; and
- Indirect CO_2 and criteria air pollutant emissions associated with transport of refrigerant to a reclamation or destruction facility.

For each of the three scenarios, the following cost impacts are evaluated:

- Costs associated with transporting refrigerant to a reclamation or destruction facility;
- Costs associated with labor time to handle refrigerant en route to a reclamation or destruction facility;
- Costs associated with the energy consumed during the destruction and reclamation process (e.g., $/kWh).

No capital costs associated with recovery equipment or reclamation/destruction equipment is assumed in this analysis, given that existing infrastructure is in place.

The remainder of this section summarizes the key assumptions used to develop this analysis.

II.3.1. Basic Assumptions

Functional Unit

In this analysis, the functional unit is one refrigeration system that falls under one of the equipment type categories defined in Table II-2.

II.3.2. Number of Disposed Units

The key assumptions used to develop the 2010 baseline are presented in Table II-3. Specifically, Table II-3 presents the number of equipment installed and reaching EOL in 2010, as well as the assumed equipment lifetime, average charge size, and amount of refrigerant (in pounds) reaching EOL assuming a full charged at time of disposal.[48] Population growth is used as a proxy for projecting equipment growth through 2050; therefore, growth in the number of units installed and the number of units reaching EOL is assumed to be 1.3% per year.

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[48] Details on assumptions used to develop these baseline estimates are included in the RMP rule's Initial Statement of Reasons (ISOR), available at: http://www.arb.ca.gov/cc/reftrack/reftrack.htm. (CARB, 2009a).

Table II-3: Overview of Baseline Assumptions by Equipment Type, 2010

Equipment Type	Number of Systems in CA	Average Charge Size (lbs)/System	Average Lifetime (years)	Units Reaching EOL	Refrigerant Contained in Disposed Equipment, Assuming Full Charge (million lbs.)
Large Commercial AC					
Chillers	16,000	1,622	20	727	1.18
Unitary AC	80,000	100	15	4,833	0.48
Small Commercial AC					
Window Units	1,200,000	1.5	12	91,728	0.14
Central AC Units	2,000,000	15	15	122,867	1.86
Residential AC					
Window Units	3,800,000	1.5	12	294,704	0.44
Central AC Units	7,300,000	7.5	15	446,078	3.35
Large Commercial Refrigeration					
Condensing units	78,000	122	20	3,437	0.42
Centralized systems	39,000	786	15	2,397	1.88
Small Commercial Refrigeration	160,000	31	20	7,140	0.03
Cold Storage	6,000	2,396	20	271	0.65
Process Cooling (Industrial)	700	3,640	20	30	0.11
Other					
Stand-Alone	700,000	7.1	20	31,155	0.22
Vending	1,400,000	0.5	15	86,714	0.04
Totals	16,779,700	NA	NA	1,092,082	10.8

Based on an annual equipment growth projection of 1.3%, the quantity of refrigerant recoverable (in metric tons) from equipment reaching EOL, assuming a full charge at time of disposal, are shown in Figure II-3, assuming a full charge at equipment disposal and 100% recovery. In order to simplify the presentation of results; several of the refrigeration/AC categories were combined after analyzing emissions at a more disaggregated level (i.e., by end use). Results are shown for the following aggregated refrigeration/AC end uses: Large Commercial AC; Small Commercial AC; Residential AC; Small Commercial Refrigeration; Large Commercial Refrigeration; Cold Storage; Process Cooling; and Stand-Alone/Vending.

Figure II-3: Metric Tons of Refrigerant Recoverable at Equipment EOL,
Assuming Full Refrigerant Charge at Disposal (2010–2050)

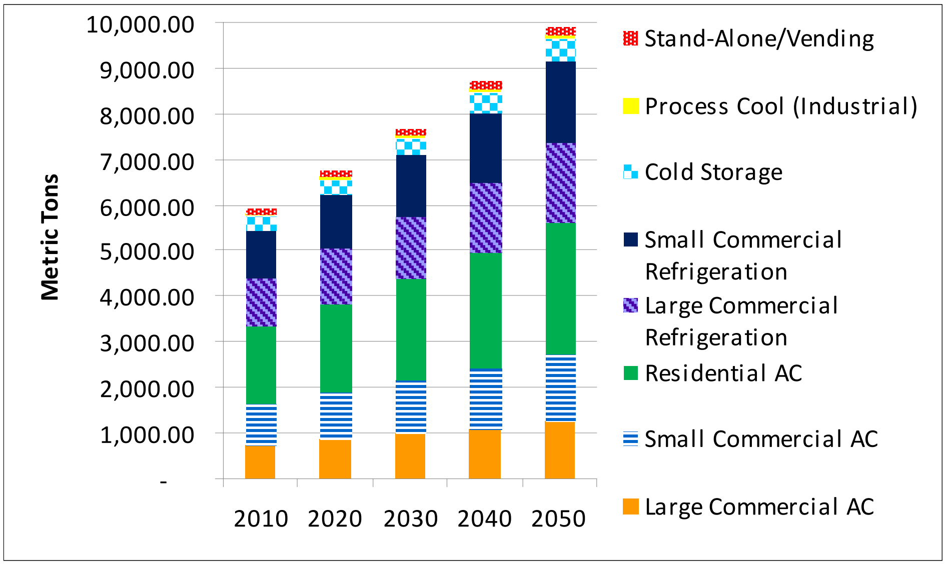

Table II-4 presents the total equivalent emission savings in 2010, in ozone depleting potential (ODP)-tons and million metric tons of carbon dioxide equivalents (MMTCO$_2$eq)—assuming equipment reaching EOL has a full charge and that 100% recovery takes place.

Table II-4: Emissions Potentially Avoided by Equipment Type, 2010

Equipment Type	Emissions Potentially Avoided	
	ODP Tons	MMTCO$_2$eq[a]
Large Commercial AC	96.48	1.39
Small Commercial AC	43.04	1.38
Residential AC	81.66	2.63
Large Commercial Refrigeration	56.82	2.41
Small Commercial Refrigeration	5.66	0.06
Cold Storage	52.81	0.92
Process Cooling (Industrial)	7.33	0.09
Stand-Alone/Vending	15.25	0.30
Totals	359.05	9.18

[a] *Global Warming Potentials are from the IPCC Second Assessment Report (SAR).*

Transport

ODS may be transported several times from recovery to ultimate destruction. For example, ODS may be transported from service companies to distributors for consolidation, and then shipped again to destruction or reclamation facilities. It is also possible that multiple shipments may occur during the consolidation process. ODS are shipped in a variety of container types (e.g., steel cylinders, bulk storage tanks, ISO containers, tanker trucks, rail cars), which can range in size from 30 lbs to 17,000 lbs. These containers are typically sent either by truck or by rail. In preparation for shipment, refrigerant may be transferred to a specific transportation container. Some storage containers, such as smaller 30-lb. cylinders, may be transported as-is, without requiring refrigerant transfer.

For simplicity, this analysis only accounts for transportation of refrigerant from one point of recovery/consolidation to the point of reclamation or destruction. Because there are approximately 10 to 20 facilities that accept ODS waste from outside sources for commercial destruction in the United States (ICF 2010b), and over 50 facilities that are EPA-certified refrigerant reclaimers—four of which are in California (U.S. EPA 2010a)—this analysis assumes that the average distance that refrigerant must travel to reach a destruction facility is 750 miles,[49] and 150 miles to reach a reclamation facility. Trucks are assumed to be 28-feet long with the capacity to transport 9,600 lbs of refrigerant per truckload.[50] Trucks are assumed to make empty return trips in all scenarios. It is assumed that trucks travel at an average speed of 50 mph.

Energy Consumption

The energy required to reclaim refrigerant varies based on distillation rates, which in turn vary based on refrigerant types (for high versus low pressure refrigerants) and level of purity. A number of refrigerant reclaimers were contacted for this study to develop energy consumption estimates for the reclamation process. Based on the information received from one of the leading reclaimers in the US, this analysis assumes an average energy consumption of 1 kWh per pound of refrigerant reclaimed.

The energy use for destroying refrigerant is assumed to be negligible, given that refrigerant destruction is likely to represent a maximum of 0.01% of a destruction facility's (e.g., cement kiln's) input feed on any given day, and that the facility is likely to operate regardless of whether ODS is destroyed or not (World Bank 2009).[51] Therefore, the costs and GHG emissions associated with the energy consumed for refrigerant destruction are not quantified in this analysis.

II.3.3. Estimating Emissions

Direct Emissions Avoidable

Direct GHG emission savings can be realized if refrigerant is recovered from equipment at EOL and then either reclaimed for reuse (to displace virgin manufacture) or safely destroyed. As described above, this analysis reviews EOL refrigerant recovery scenarios of 10%, 50%, and 90% to estimate potential emission savings through 2050. For simplicity, this analysis assumes that 100% of the refrigerant recovered and subsequently sent for reclamation or destruction is avoided from being released to the atmosphere.[52] Emission savings are estimated using global

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[49] The nearest known facility that accepts refrigerants for destruction is in Aragonite, Utah.

[50] Assuming one truck can transport 12 1,000-lb cylinders per load, and assuming each cylinder contains about 800 lbs of refrigerant. Therefore, total cargo load would be 12,000 lbs, total refrigerant capacity would be 9,600 lbs. (ARCA, 2010; JACO, 2010).

[51] In the United States, only one of the 10 to 20 known destruction facilities that accept refrigerants for commercial destruction operates exclusively for the purpose of destroying refrigerants and other ODS. This facility is located in Ohio, thousands of miles from the California market.

[52] The actual efficiency of refrigerant reclamation and destruction is not 100%; the reclamation process is estimated to be 98.5% efficient, while the TEAP Task Force on Destruction Technologies report recommends a destruction and removal efficiency (DRE) for ODS refrigerants of 99.99% (TEAP 2002).

warming potentials (GWPs) from the IPCC Second Assessment Report (SAR) and ODPs from the Montreal Protocol.

Indirect GHG and Criteria Pollutant Emissions from Transport

Indirect emissions of CO_2 and criteria pollutants associated with transport will vary based on the distances traveled for reclamation (150 miles) or destruction (750 miles).

Table II-5 presents the assumed fuel efficiency of trucks carrying refrigerant sent for reclamation or destruction and the resulting emissions assumed per mile. Diesel fuel is assumed to have a lower heating value (LHV) of 135.5 MJ/gal and a CO_2eq emission factor of 94.7 g CO_2eq/MJ, based on GREET 1.8b used for the California Low Carbon Fuel Standard (CARB 2009b).[53]

Table II-5: Truck Fuel Efficiency and Emissions per Mile (kgCO_2eq/mile), Based on U.S. EPA's PERE-HD

Load	Quantity of Refrigerant Per Truckload (lbs)	Total Truckload Cargo Weight (lbs)	Fuel Efficiency[a]	Emissions per Mile (kgCO_2eq/mile)
Refrigerant	9,600	12,000	7.2	1.78

[a] Fuel Efficiency is based on the U.S. EPA (2010b) PERE-HD Calculator

Criteria pollutant emissions associated with transport are based on the emission factors presented in Table II-6, based on Façanha and Horvath (2007). It should be noted that criteria air pollutant emission factors reflect global emission estimates; due to analytical limitations, emissions for criteria air pollutants could not be disaggregated for California specific regions or air districts.

Table II-6: Criteria Pollutant Transport Emission Factors (g/mile)[a]

Load	NO_x	PM10	PM2.5	SO_2
Refrigerant	14.49	0.40	0..07	0.37

[a] Emission factors account for fuel combustion and pre-combustion.
Source: Façanha and Horvath (2007).

Indirect Emissions from Energy Consumption

Table II-7 presents the emission factors used to calculate indirect GHG and criteria pollutant emissions associated with the energy consumed during the reclamation process.

Table II-7: Emission Factors Associated with Energy Consumption

	Energy Consumption Emission Factors (g/kWh)				
	g CO_2eq/kWh[a]	g NO_x/kWh	g PM10/kWh	g PM2.5/kWh	g SO_x/kWh
Energy Consumption	751.50	1.18	1.02	0.27	2.60

[a] *The CO_2eq emission factor represents net CO_2, which includes CO_2, CO, and VOCs.*
Source: GREET 1.8c.

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[53] The CO_2eq emission factor for diesel fuel includes well to tank (WTT) and tank-to-wheel energy and greenhouse gas values and vehicle fuel emissions for California Ultra Low-Sulfur Diesel (ULSD).

II.3.4. Estimating Costs

In this analysis, the following annual costs and cost savings are quantified:

- Refrigerant Costs/Savings
- Transport Costs
- Energy Costs
- Labor Costs.

The assumptions are described below.

Refrigerant Reclamation and Destruction

The value of used refrigerant sent for reclamation is highly variable, depending on the level of purity of the used refrigerant as well as the market demand (value) for that particular type of refrigerant. As ODS refrigerants (e.g., HCFC-22) are phased out, their market values will increase with scarcity. Recently, HFC-134a has been in an over-supply situation, and therefore does not have value when returned for reclamation. Conversely, the value of used CFC-11 is estimated to range from $1.00-$3.00/lb, based on information received from one of the largest reclaimers in the US. While the values of refrigerants will vary over time and by refrigerant type, this analysis assumes a cost savings of $1.00/lb. for all refrigerants returned for reclamation.

The price charged to customers for refrigerant destruction varies depending on a variety of factors, including gas type, volume, and whether or not the customer is long-term or short-term. However, although costs vary depending on many different factors, costs of destruction are relatively uniform across all applications, and are not primarily substance-driven (i.e., CFC/HCFC/HFCs) (TEAP 2009). Globally, ODS destruction costs range between roughly $1 and $6 per pound, with an average of roughly $3.50/lb (MLF 2008). Long-term customers sending large quantities of refrigerants on a regular basis will generally be charged less—between $0.50 and $2.00 per pound, with a median price of $1.25/lb. For this analysis, it is assumed that the cost associated with refrigerant destruction is $2.50/lb.

However, it is possible that destruction costs are converted into cost savings if destruction is performed as part of a carbon offset project; ODS destruction projects are now eligible for carbon credits under a number of standards in the voluntary carbon market, including the Climate Action Reserve. Recently, the price of carbon offset credits on the Reserve, known as Climate Reserve Tonnes (CRTs), has ranged from $4.50 to $10.00 per metric ton of carbon dioxide equivalent ($MTCO_2eq$). Assuming a carbon price of $7.50/$tCO_2$eq. and based on the Reserve's current ODS project protocol, the destruction of 1,000 pounds of CFC-12 refrigerant could earn over $31,500 in credit revenue,[54] although project costs (e.g., registration, administration, verification, etc.) could be significant and would lower total value.

Refrigerant Recovery Cost

The cost associated with ODS recovery from refrigeration/AC equipment depends on the time required to complete the recovery process. More time will be required to recover refrigerant from smaller equipment, due to a lower economy of scale (i.e., inherent inefficiencies compared to recovering refrigerant from fewer, larger systems). TEAP (2009) estimates a refrigerant recovery cost of approximately $2.70- $3.60 per lb. This analysis assumes a cost of $3.00 per lb.

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[54] This value assumes a 15% CO_2eq discounting.

Transport Cost

Costs associated with transporting ODS to a destruction facility can vary greatly depending on distance and quantity, and whether the transport is within or beyond state borders. Domestically, bulk quantities in-state are the most economical to transport. According to one destruction company, a railcar carrying 190,000 pounds of waste-containing ODS costs approximately $800 for in-state shipments (about $0.42 per 100 pounds of ODS); these costs approximately double for out-of-state shipments. The same source estimates that a tank truck carrying 42,000 pounds of waste can cost as much as $700 for in-state shipments ($1.67 per 100 pounds); corresponding prices for out-of-state shipments were not provided by the source, as they are highly variable. Another destruction company reported the cost to transport waste refrigerant varies from $0.15 to $0.30 per pound, depending on the refrigerant type. Another company charges $4.00 per mile for transport in a pressurized ISO tanker, or the tanker can be leased (with a minimum 1-year lease) for $1,000 per month (ICF 2010b). According to TEAP (2009), the international average cost of transporting ODS between 100 to 600 miles ranges from $0.004 to $0.03 per pound of ODS.

For this analysis, transport costs are estimated based on fuel and labor costs. Specifically, fuel costs are based on an assumed diesel price of $2.54/gallon[55] and an average fuel efficiency of 8.75 mpg (averaging 7.2 mpg for loaded trip to facility and 10.3 mpg for empty return trip). This translates to a round-trip average cost of $0.29 per mile, which in turn translates to a fuel cost of $0.01 per lb. of refrigerant sent for reclamation, or $0.05 per lb. of refrigerant sent for destruction.

Transport labor is estimated based on an assumed labor rate of $75/hour. As discussed above, this analysis assumes that trucks carrying the recovered refrigerant must travel 750 miles to reach a destruction facility and 150 miles to reach a reclamation facility, and that they travel at approximately 50 mph. Therefore, the labor time required to transport refrigerant to a destruction facility translates to $0.23/lb, and $0.05/lb for transport to a reclamation facility.

The transport costs assumed in this analysis may be conservative, as actual transport costs may be lower depending on the size of bulk container that is used. As discussed above, ISO containers can reach a size of 17,000 lbs. Transporting refrigerant in containers of this size would be more economical per pound of refrigerant than transporting in the smaller 9,600 lb containers that used in the calculations for this analysis.

Energy Costs

Costs associated with the energy consumed during both the destruction and reclamation process is based on an estimated electricity cost of $0.11/kWh.

Capital Costs

No capital costs are assumed in this analysis, as infrastructure (i.e., refrigerant recovery equipment, reclamation facilities, and destruction facilities) is already in place.

II.4. 4. Costs and Benefits

This section presents the estimated costs and benefits of each recovery scenario, as well as the cost-effectiveness in terms of $/MTCO$_2$eq.

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[55] Fuel prices are based on US estimates provided at: http://tonto.eia.doe.gov/oog/info/wohdp/diesel.asp. Price is accurate as of July 2009.

II.4.1. Costs

Potential costs associated with refrigerant recovery and subsequent reclamation or destruction are presented for the different recovery scenarios (10%, 50%, and 90%) in Table II-8, Table II-9, and Table II-10, respectively. An annual discount rate of 5% is applied to all scenarios. This discount rate was chosen for consistency with other ARB analyses. It should be noted that the estimated net costs associated with refrigerant destruction may actually be cost *savings*, if refrigerant destruction is performed as part of a carbon offset project.

Table II-8: Total Estimated Costs for Recovery, Reclamation and Destruction, Assuming 10% Recovery Scenario

Year	Refrigerant Recovery	Recovery and Reclamation				Recovery and Destruction		
		Energy Consumption	Transport (Labor & Fuel)	Value of Used Refrigerant (Cost Savings)	Net Cost	Transport (Labor & Fuel)	Refrigerant Destruction	Net Cost
2010	$3,239,801	$ 118,973	$60,418	$1,079,934	$2,339,079	$302,092	$2,699,834	$6,241,728
2020	$3,695,982	$135,519	$68,926	$1,231,994	$2,668,433	$344,628	$3,079,985	$7,120,596
2030	$4,208,339	$154,306	$78,481	$1,402,780	$3,038,346	$392,403	$3,506,949	$8,107,690
2040	$4,772,321	$174,985	$88,998	$1,590,774	$3,445,531	$444,991	$3,976,934	$9,194,246
2050	$5,424,933	$198,914	$101,169	$1,808,311	$3,916,705	$505,843	$4,520,777	$10,451,553
Total (NPV)	$67,529,831	$2,476,094	$1,259,351	$22,509,944	$48,755,332	$6,296,755	$56,274,859	$130,101,446

Table II-9: Total Estimated Costs for Recovery, Reclamation and Destruction, Assuming 50% Recovery Scenario[a]

Year	Refrigerant Recovery	Recovery and Reclamation				Recovery and Destruction		
		Energy Consumption	Transport (Labor & Fuel)	Value of Used Refrigerant (Cost Savings)	Net Cost	Transport (Labor & Fuel)	Refrigerant Destruction	Net Cost
2010	$16,199,006	$593,964	$302,092	$5,399,669	$11,695,393	$1,510,461	$13,499,171	$31,208,638
2020	$18,479,912	$677,597	$344,628	$6,159,971	$13,342,166	$1,723,142	$15,399,927	$35,602,980
2030	$21,041,694	$771,529	$392,403	$7,013,898	$15,191,728	$1,962,013	$17,534,745	$40,538,452
2040	$23,861,605	$874,926	$444,991	$7,953,868	$17,227,653	$2,224,953	$18,884,671	$45,971,229
2050	$27,124,665	$994,571	$505,843	$9,041,555	$19,583,524	$2,529,214	$22,603,887	$52,257,766
Total (NPV)	$337,649,156	$12,380,469	$6,296,755	$112,549,719	$243,776,662	$31,483,774	$281,374,297	$650,507,228

Table II-10: Total Estimated Costs for Recovery, Reclamation and Destruction, Assuming 90% Recovery Scenario

Year	Refrigerant Recovery	Recovery and Reclamation				Recovery and Destruction		
		Energy Consumption	Transport (Labor & Fuel)	Value of Used Refrigerant (Cost Savings)	Net Cost	Transport (Labor & Fuel)	Refrigerant Destruction	Net Cost
2010	$29,158,210	$1,069,134	$543,766	$9,719,403	$20,526,339	$2,718,830	$24,298,509	$56,175,548
2020	$33,263,841	$1,219,674	$620,331	$11,087,947	$23,416,556	$3,101,655	$27,719,868	$64,085,364
2030	$37,875,050	$1,388,752	$706,325	$12,625,017	$26,662,682	$3,531,623	$31,562,542	$72,969,214
2040	$42,950,890	$1,574,866	$800,983	$14,316,963	$30,235,892	$4,004,915	$35,792,408	$82,748,212
2050	$48,824,397	$1,790,228	$910,517	$16,274,799	$34,370,632	$4,552,584	$40,686,997	$94,063,978
Total (NPV)	$607,768,482	$22,284,844	$11,334,159	$202,589,494	$427,847,305	$56,670,793	$506,473,735	$1,170,913,010

II.4.2. Benefits

The GHG emissions savings potential associated of refrigerant recovery and subsequent reclamation or destruction are presented for each recovery scenario (10%, 50%, and 90%) in Table II-11, Table II-12, and Table II-13, respectively. The GHG emissions savings potential is shown graphically in Figure II-4. As shown, a 90% refrigerant recovery scenario at equipment EOL is estimated to result in an incremental savings of over 433 $MMTCO_2eq$ by 2050, compared to a modest recovery scenario of only 10%.

Table II-11: Estimated GHG Benefits, Assuming 10% Recovery ($MTCO_2eq$)

Year	Recovery		Recovery and Reclamation[a]			Recovery and Destruction[a]		
	Direct GHG Emissions Avoidable from Refrigerant Recovery		Indirect GHG Emissions from Energy Consumption	Indirect GHG Emissions from Transport	Net GHG Emissions Avoided	Indirect GHG Emissions from Energy Consumption	Indirect GHG Emissions from Transport	Net GHG Emissions Avoided
	ODS	HFC						
2010	649,611	268,265	811	60	917,005	NA	300	917,575
2020	167,234	955,255	925	69	1,121,496	NA	343	1,122,147
2030	284	1,339,935	1,053	78	1,339,087	NA	390	1,339,829
2040	—	1,517,587	1,195	88	1,516,304	NA	442	1,517,145
2050	—	1,721,782	1,358	101	1,720,369	NA	503	1,721,325
Total	4,596,731	49,539,782	43,598	3,229	54,089,685	NA	16,146	54,120,366

NA= Not applicable; the energy use for destroying refrigerant is assumed to be negligible, given that refrigerant destruction is likely to represent a maximum of 0.01% of a destruction facility's (e.g., cement kiln's) input feed on any given day, and that the facility is likely to operate regardless of whether ODS is destroyed or not (World Bank 2009).

[a] Total GHG benefits associated with the recovery and reclamation/destruction of ODS and HFCs combined.

Table II-12: Estimated GHG Benefits, Assuming 50% Recovery (MTCO$_2$eq)

Year	Recovery		Recovery and Reclamation[a]			Recovery and Destruction[a]		
	Direct GHG Emissions Avoidable from Refrigerant Recovery		Indirect GHG Emissions from Energy Consumption	Indirect GHG Emissions from Transport	Net GHG Emissions Avoided	Indirect GHG Emissions from Energy Consumption	Indirect GHG Emissions from Transport	Net GHG Emissions Avoided
	ODS	HFC						
2010	3,248,056	1,341,323	4,055	300	4,585,023	NA	1,502	4,587,877
2020	836,170	4,776,276	4,626	343	5,607,478	NA	1,713	5,610,733
2030	1,4200	6,699,674	5,267	390	6,695,436	NA	1,951	6,699,143
2040	—	7,587,937	5,973	442	7,581,521	NA	2,212	7,585,725
2050	—	8,609,139	6,790	503	8,601,846	NA	2,515	8,606,624
Total	22,983,653	247,698,909	217,991	16,146	270,448,425	NA	80,731	270,601,831

NA= Not applicable; the energy use for destroying refrigerant is assumed to be negligible, given that refrigerant destruction is likely to represent a maximum of 0.01% of a destruction facility's (e.g., cement kiln's) input feed on any given day, and that the facility is likely to operate regardless of whether ODS is destroyed or not (World Bank 2009).

[a] Total GHG benefits associated with the recovery and reclamation/destruction of ODS and HFCs combined.

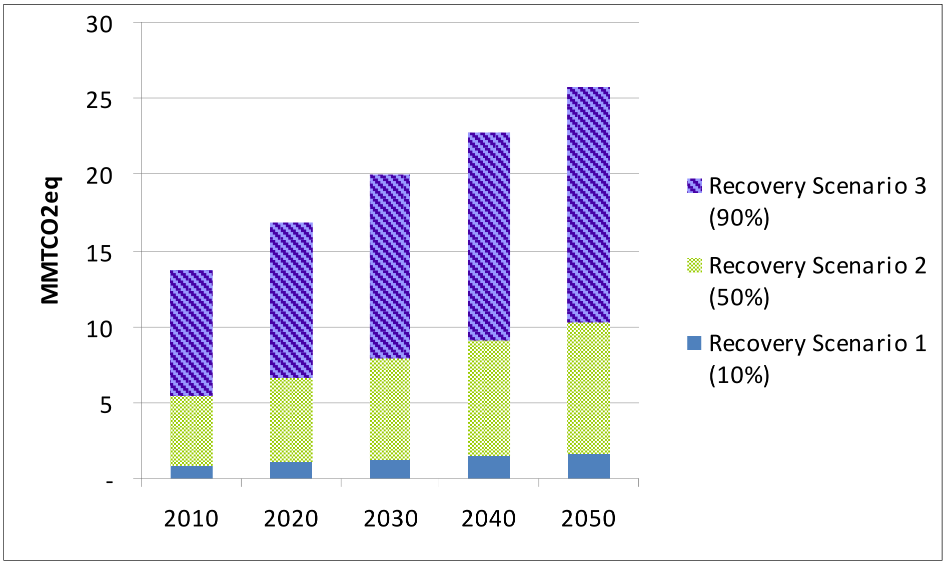
Table II-13: Estimated GHG Benefits, Assuming 90% Recovery (MTCO$_2$eq)

Year	Recovery		Recovery and Reclamation[a]			Recovery and Destruction[a]		
	Direct GHG Emissions Avoidable from Refrigerant Recovery		Indirect GHG Emissions from Energy Consumption	Indirect GHG Emissions from Transport	Net GHG Emissions Avoided	Indirect GHG Emissions from Energy Consumption	Indirect GHG Emissions from Transport	Net GHG Emissions Avoided
	ODS	HFC						
2010	5,856,501	2,414,381	7,299	541	8,253,042	NA	2,703	8,258,179
2020	1,505,107	8,597,297	8,327	617	10,093,460	NA	3,084	10,099,320
2030	2,556	12,059,413	9,481	702	12,051,785	NA	3,511	12,058,457
2040	—	13,658,287	10,752	796	13,646,738	NA	3,982	13,654,305
2050	—	15,496,451	12,222	905	15,483,323	NA	4,526	15,491,924
Total	41,370,575	445,858,036	392,383	29,063	486,807,165	NA	145,315	487,083,296

NA= Not applicable; the energy use for destroying refrigerant is assumed to be negligible, given that refrigerant destruction is likely to represent a maximum of 0.01% of a destruction facility's (e.g., cement kiln's) input feed on any given day, and that the facility is likely to operate regardless of whether ODS is destroyed or not (World Bank 2009).

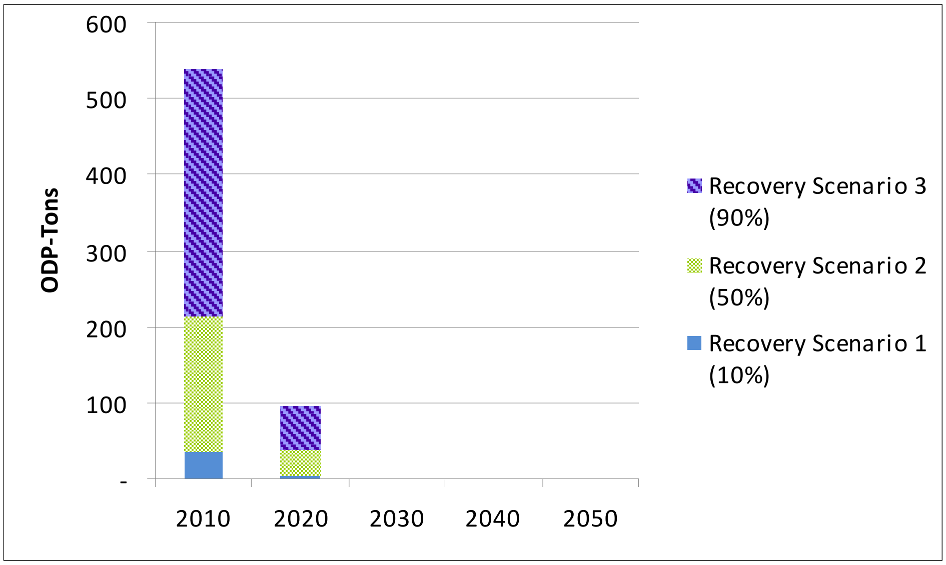
[a] Total GHG benefits associated with the recovery and reclamation/destruction of ODS and HFCs combined.

Figure II-4: Potential Emissions Savings by Recovery Scenario through 2050 ($MMTCO_2eq$)



In addition to the GHG benefits presented above, stratospheric ozone benefits will also result, as summarized in Figure II-5.

Figure II-5: Potential Emissions Savings by Recovery Scenario through 2050 (ODP-tons)



While environmental benefits are associated with refrigerant recovery and subsequent reclamation or destruction at equipment EOL, slight environmental disbenefits result from an increase in criteria pollutant emissions associated with additional transport requirements for refrigerant reclamation and destruction, as presented in Table II-14 and Table II-15, respectively.

Table II-14: Estimated Criteria Pollutant Emissions (MT) Associated with Reclamation

Year	10% Recovery/Reclamation				50% Recovery/Reclamation				90% Recovery/Reclamation			
	NO_x	SO_x	PM10	PM2.5	NO_x	SO_x	PM10	PM2.5	NO_x	SO_x	PM10	PM2.5
2010	0.49	0.01	0.01	0.00	2.45	0.06	0.07	0.01	4.40	0.11	0.12	0.02
2020	0.56	0.01	0.02	0.00	2.79	0.07	0.08	0.01	5.02	0.13	0.14	0.02
2030	0.64	0.02	0.02	0.00	3.18	0.08	0.09	0.02	5.72	0.15	0.16	0.03
2040	0.72	0.02	0.02	0.00	3.60	0.09	0.10	0.02	6.48	0.17	0.18	0.03
2050	0.82	0.02	0.02	0.00	4.09	0.10	0.11	0.02	7.37	0.19	0.20	0.04
2010–2050	26.29	0.67	0.73	0.13	131.44	3.36	3.63	0.63	236.59	6.04	6.53	1.14

Table II-15: Estimated Criteria Pollutant Emissions (MT) Associated with Destruction

Year	10% Recovery/Reclamation				50% Recovery/Reclamation				90% Recovery/Reclamation			
	NO_x	SO_x	PM10	PM2.5	NO_x	SO_x	PM10	PM2.5	NO_x	SO_x	PM10	PM2.5
2010	2.45	0.06	0.07	0.01	12.23	0.31	0.34	0.06	22.01	0.56	0.61	0.11
2020	2.79	0.07	0.08	0.01	13.95	0.36	0.38	0.07	25.10	0.64	0.69	0.12
2030	3.18	0.08	0.09	0.02	15.88	0.41	0.44	0.08	28.58	0.73	0.79	0.14
2040	3.60	0.09	0.10	0.02	18.01	0.46	0.50	0.09	32.41	0.83	0.89	0.16
2050	4.09	0.10	0.11	0.02	20.47	0.52	0.57	0.10	36.85	0.94	1.02	0.18
2010–2050	131.44	3.36	3.63	0.63	657.18	16.78	18.14	3.17	1,182.93	30.21	32.66	5.71

Cost Effectiveness

The incremental costs per GHG emission reduction of refrigerant recovery and subsequent reclamation or destruction are presented in Table II-16, as well as the associated net present values (assuming a 5% discount rate). While this analysis does not vary costs by year or refrigerant type, the benefits vary based on the mix of refrigerants projected to be available for recovery at equipment EOL. As a result, cost-effectiveness varies over time. As shown, annual cost effectiveness for ODS and HFCs combined varies from over \$2/MTCO$_2$eq for recovery/reclamation to roughly \$6/MTCO$_2$eq for recovery/destruction, with reclamation being more cost-effective due to the value of returned used refrigerant. Furthermore, as shown, the incremental cost of reducing GHG emissions from the recovery of ODS is higher than that for HFCs across the time series. This is due to the fact that by 2010, all CFC-containing equipment is assumed to have reached full retirement, meaning that only HCFC refrigerants—with lower GWPs—are available at equipment EOL. Moreover, from 2029 through 2039, the primary ODS refrigerant remaining in equipment (i.e., chillers) is assumed to be HCFC-23, which has a very low GWP of 90; this causes a sharp increase in the cost per MTCO$_2$eq for recovery, reclamation, and/or destruction. By 2040, it is assumed that equipment containing HCFCs will have fully reached retirement. It should be noted, however, that if ODS refrigerant destruction is performed as part of a carbon offset project, the cost-effectiveness of ODS destruction could be much higher.

Table II-16: Cost Effectiveness of GHG Reductions ($/MTCO$_2$eq) 2010-2050

Year	ODS			HFC			Total (ODS + HFC)		
	Recovery	Recovery/ Reclamation	Recovery/ Destruction	Recovery	Recovery/ Reclamation	Recovery/ Destruction	Recovery	Recovery/ Reclamation	Recovery/ Destruction
2010	$3.84	$2.78	$7.41	$2.77	$2.00	$5.34	$3.53	$2.55	$6.80
2020	$4.51	$3.26	$8.70	$3.08	$2.22	$5.93	$3.29	$2.38	$6.35
2030	$73.49	$54.13	$142.55	$3.13	$2.26	$6.02	$3.14	$2.27	$6.05
2040	NA	NA	NA	$3.14	$2.27	$6.06	$3.14	$2.27	$6.06
2050	NA	NA	NA	$3.15	$2.28	$6.07	$3.15	$2.28	$6.07
2010–2050 NPV	$3.29	$2.37	$6.33	$1.06	$0.76	$2.04	$1.25	$0.90	$2.40

II.5. Discussion of Findings

Table II-17 summarizes the estimated total costs and GHG emissions avoided by recovery scenario from 2010 to 2050, as well as the costs associated with refrigerant recovery, reclamation, and destruction.

Table II-17: Total Incremental Costs and GHG Emissions Avoided by Scenario (2010-2050)[a]

Total Costs and GHG Emissions Avoided	10% Recovery	50% Recovery	90% Recovery
GHG Emissions Avoided (MMTCO$_2$eq)	54.1	270.6	487.1
Cost of Recovery ($ million)	67.5	337.6	607.8
Cost of Recovery and Reclamation ($ million)	48.8	243.8	427.8
Cost of Recovery and Destruction ($ million)	130.1	650.5	1,170.9

As shown, refrigerant recovery can result in significant GHG emission savings from 2010-2050. By achieving a 90% recovery rate in lieu of only 10%, the release of 433 MMTCO$_2$eq can be avoided from 2010 through 2050. Recovery at equipment EOL is most critical from the residential AC subsector, as this end-use is projected to have the greatest share of refrigerant installed in equipment expected to reach EOL through 2050 (see Figure II-3 and Table II-4). Large commercial refrigeration and small/large commercial AC are also critical end-uses for recovery at equipment EOL.

II.6. Recommendations

While refrigerant recovery is required by federal law, ARB can consider regulatory and non-regulatory options for promoting refrigerant recovery at equipment EOL, particularly in key subsectors (i.e., residential AC, large commercial refrigeration, and commercial AC). In particular, the following options should be considered:

- *Promotion of tradable credit/certificate system*—The recovery and destruction of refrigerant is eligible for carbon credits on certain voluntary markets (e.g., the Climate Action Reserve). Given the high costs associated with refrigerant destruction, ARB could promote the development of offset projects in order to create economic incentives for destruction. This could be achieved through stakeholder education and coordination efforts.
- *Taxes on virgin refrigerant sales and rebates on the return of used refrigerants for destruction*—To create a financial incentive for refrigerant recovery, a tax can be placed on

virgin and reclaimed ODS/HFC refrigerant placed on the market. The revenue from the tax could be used to offer a rebate on the return of recovered ODS/HFC refrigerants. A number of countries have implemented this type of scheme, including Norway, France, and Australia, and it has resulted in increased amounts of refrigerants returned for reclamation/destruction. For example, the 2006 report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (RTOC 2006) reports that in France, where reclaimed refrigerant totals have been gathered, there has been a significant increase in the efficiency of the recovery program. In 1992, without any regulation, only 200 metric tons of recovered refrigerant (CFCs and HCFCs) were reclaimed. In 1993, after making recovery mandatory and carrying out a deposit-refund scheme, the quantity grew to 300 metric tons, and the number of refrigeration companies concerned doubled from 200 to 400 (out of 2,500). Government incentives were necessary to reach full development of recovery schemes.

- *Producer Responsibility Scheme*—Producer responsibility schemes, be they voluntary or mandated by law, can also be used to promote the recovery and destruction of refrigerants. For example, refrigerant producers could offer take-back programs for unwanted chemicals for the purpose of reclamation or destruction and/or establish centralized collection points for refrigerant prior to destruction; this would allow users to return unwanted refrigerants to producers via distributors at a low or no cost. In many cases, chemical producers would be able to reclaim the used refrigerant more cost-effectively than they can produce virgin chemical.

Due to time constraints, a number of simplifications were made in this analysis. A more complete LCA would require additional considerations and a more nuanced methodology. These considerations include:

- Actual values (cost savings) associated with used refrigerant sent for reclamation will vary significantly by refrigerant type and over the 40-yr time horizon of this analysis.
- The energy consumed during the reclamation process is not yet quantitatively considered in this analysis, due to data limitations. While future updates to this report will include an average estimate for energy consumption for the reclamation process, actual energy consumption rates will vary by refrigerant type.

II.7. References

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II.8. Appendix: Report Figures Presented as Data

The following tables show the data which ICF used to develop the figures and graphs used throughout Part II. LCA on Other Stationary Refrigeration/Air-Conditioning Equipment Reaching End-of-Life. In each case, table numbers are followed by a figure reference in brackets (from Figure II-xx), and the title of the relevant figure as it is shown in the body of the report.

Table II-18 (from Figure II-1): Projected Emissions from the Refrigeration/AC Sector in 2020 Following Implementation of ARB's Refrigerant Management Rule

End Use	Projected Emissions (MMTCO2eq)	%
Large Commercial AC	1.11	6%
Small Commercial AC	3.77	19%
Residential AC	7.01	35%
Small Commercial Refrigeration	0.48	2%
Large Commercial Refrigeration	5.10	26%
Cold Storage	1.99	10%
Process Cooling (Industrial)	0.09	0.4%
Stand-Alone/Vending	0.30	2%
Total	19.84	100%

Table II-19 (from Figure II-2): Total Projected Emissions of ODS and HFC Refrigerants Following Implementation of ARB's Refrigerant Management Rule

Year	Projected ODS Emissions (MMTCO$_2$eq)	Projected HFC Emissions (MMTCO$_2$eq)
2010	16.35	6.61
2011	15.19	8.09
2012	14.07	9.56
2013	13.00	11.03
2014	12.00	12.50
2015	11.04	13.98
2016	9.45	13.66
2017	8.58	15.00
2018	7.21	14.28
2019	6.43	15.54
2020	5.32	14.52
2021	4.50	15.82
2022	3.78	17.05
2023	3.13	18.22
2024	2.52	19.34
2025	1.96	20.39
2026	1.46	21.38
2027	1.06	22.29
2028	0.72	23.10
2029	0.42	23.81

Year	Projected ODS Emissions (MMTCO$_2$eq)	Projected HFC Emissions (MMTCO$_2$eq)
2030	0.17	24.49
2031	0.13	24.95
2032	0.09	25.38
2033	0.06	25.81
2034	0.04	26.24
2035	0.02	26.66
2036	0.01	27.06
2037	0.00	27.47
2038	0.00	27.88
2039	0.00	28.31
2040	0.00	28.74
2041	0.00	29.17
2042	0.00	29.61
2043	0.00	30.06
2044	0.00	30.52
2045	0.00	30.98
2046	0.00	31.45
2047	0.00	31.93
2048	0.00	32.41
2049	0.00	32.91
2050	0.00	33.39

Table II-20 (from Figure II-3): Metric Tons of Refrigerant Recoverable at Equipment EOL, Assuming Full Refrigerant Charge at Disposal (2010-2050)

End Use	2010	2020	2030	2040	2050
Large Commercial AC	756	881	997	1,110	1,255
Small Commercial AC	904	1,028	1,170	1,332	1,515
Residential AC	1,718	1,955	2,224	2,531	2,880
Large Commercial Refrigeration	13	14	16	19	21
Small Commercial Refrigeration	1,045	1,189	1,353	1,539	1,751
Cold Storage	293	326	381	433	493
Process Cooling (Industrial)	50	57	64	73	83
Stand-Alone/Vending	121	137	156	178	202

Table II-21 (from Figure II-4): Potential Emissions Savings by Recovery Scenario through 2050 (MMTCO$_2$eq)

Year	Recovery Scenario 1 (10%)	Recovery Scenario 2 (50%)	Recovery Scenario 3 (90%)
2010	0.9	4.6	8.2
2020	1.1	5.6	10.1
2030	1.3	6.7	12.1
2040	1.5	7.6	13.4
2050	1.7	8.6	15.5

Table II-22 (from Figure II-5): Potential Emissions Savings by Recovery Scenario through 2050 (ODP-tons)

Year	Recovery Scenario 1 (10%)	Recovery Scenario 2 (50%)	Recovery Scenario 3 (90%)
2010	35.9	179.5	323.1
2020	6.4	32.0	57.6
2030	0.1	0.3	0.6
2040	—	—	—
2050	—	—	—

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III. LCA on Disposable Refrigerant Cylinders

III.1. Introduction

III.1.1. Background

Under the California Global Warming Solutions Act of 2006 (AB 32), the Air Resources Board (ARB) is required to limit statewide greenhouse gas (GHG) emissions to 1990 levels by 2020. To help attain the legislated emission reductions requirements, ARB has identified potential measures intended to reduce emissions of high global warming potential (GWP) gases. Significant emissions of high GWP gases result from the release of refrigerants commonly used in motor vehicle air conditioning (MVAC) and stationary refrigeration/air conditioning (AC) equipment. Therefore, ARB has identified refrigerant emissions from refrigerant cylinders for further study to determine the cost and benefit of alternative refrigerant cylinder management scenarios. Specifically, ARB has commissioned a lifecycle analysis on the use and disposal of 30-pound cylinders used to transport ozone depleting substances (ODS) and/or high-GWP refrigerants (e.g., HCFC-22, and HFC-134a) for servicing refrigeration/AC equipment. The results of the lifecycle analysis are contained in this section of the research report.

Based on national cylinder sales, an estimated 732,350 disposable cylinders are used annually for MVAC and stationary refrigeration/AC service and repair operations in California (Airgas 2007, 2009). Once the refrigerant is used and the cylinder is designated as "empty," disposable cylinders may be stored, recycled, landfilled, or otherwise discarded. Any residual refrigerant is eventually emitted from these cylinders, most commonly by puncturing or drilling a hole in the cylinder to release any residual gas ("the heel") prior to shredding or landfilling. Based on an assumed average heel of 1.85% (Perrin Quarles Associates 2007), ARB (2008) estimated current "heel" emissions from disposable cylinders to range from 0.25 to 0.31 million metric tons of carbon dioxide equivalent (MMTCO$_2$eq) per year. This demonstrates the significant emission reductions that could be achieved through improved management of spent disposable cylinders, including refrigerant heel recovery and cylinder recycling practices.

To achieve emission reductions from this source, in December 2009, ARB adopted various control measures, including mandating cylinder evacuation prior to recycling or disposal down to a 15-inch mercury vacuum, relative to standard atmospheric pressure of 29.9 inches of mercury. Evacuating refrigerant cylinders would remove all but 0.2% (approximately 0.05 lbs) of the leftover refrigerant heel normally remaining after the cylinder is used, resulting in annual emissions of 0.025 MMTCO$_2$eq per year.

ARB considered, but did not adopt a control measure banning the use of disposable 30-lb. cylinders and requiring the use of refillable cylinders instead. Under such a measure, refillable cylinders would have been returned after use for refilling and reuse, thereby avoiding the release of the refrigerant heel and other GHG emissions associated with the production of virgin cylinders each year.

Note that if 100% compliance with the ARB refrigerant cylinder evacuation requirements is achieved, additional cylinder management options will not be necessary. However, this LCA study was commissioned prior to adoption to the ARB refrigerant regulations, and therefore focuses on alternative cylinder management scenarios for analysis.

III.1.2. Purpose

This analysis aims to evaluate the environmental benefits and costs associated with (a) refrigerant evacuation from disposable cylinders prior to disposal (which has been incorporated into the CARB stationary refrigerant management rule adopted in December 2009), and (b) the banning of disposable cylinders (which will be studied to compare its cost-benefit with that of the CARB-required refrigerant evacuation of spent cylinders). To this end, the analysis estimates the lifecycle emissions and costs associated with current cylinder use and disposal, as well as the incremental costs and emission reductions associated with replacing the disposable cylinder fleet with refillables over a five-year phase-in period.

The remainder of the report is organized as follows:

- *Section 2* describes the baseline, assumptions regarding cylinder manufacture, use, and disposal, and the established boundary for the lifecycle assessment;
- *Section 3* describes the alternative management scenario;
- *Section 4* reviews key assumptions regarding the number and design of cylinders, heel and transportation emission factors, and associated costs;
- *Section 5* examines the costs associated with the BAU and the refillables management scenario, focusing on labor, transport, manufacturing, recycling, and recovery equipment costs;
- *Section 6* analyzes the emissions associated with the BAU and the emission reductions associated with the refillables management scenario;
- *Section 7* summarizes the incremental costs and emissions reductions in \$/MTCO$_2$eq from 2010 to 2050;
- *Section 8* presents recommendations and additional considerations;
- *Section 9* presents the references;
- *Appendix A* presents a review of cylinder evacuation times, vacuum pressures, and refrigerant heels;
- *Appendix B* presents a qualitative review of a potential refund/deposit program that could be established to encourage compliance with existing non-refillable cylinder heel recovery regulations;
- *Appendix C* presents best management practices; and
- *Appendix D* presents report figures as data.

III.2. Description of Current State (Business as Usual)

Approximately 6 million 30-pound refrigerant cylinders are sold annually in the United States (Airgas 2007, 2009). Disposable cylinders constitute well over 90% of all 30-lb. cylinders sold in the country each year, although larger (50-200 lb.) refillable refrigerant cylinders are commonly used (Airgas 2009, Hudson 2009, Berkan 2009). Of the 6 million 30-lb. disposable cylinders sold, an estimated 1 million are used in the automotive sector[56] and the remaining 5 million are used in the stationary refrigeration/air conditioning (AC) sector. Based on California's population, there are an estimated 732,350 disposable cylinders sold each year in California. Cylinder sales fluctuate with the general market conditions, and are currently stagnant or possibly shrinking due to the economic downturn (Airgas 2009).

Disposable refrigerant cylinders sold in California are currently manufactured by three U.S. companies operating in Illinois, Indiana, Kentucky, Maryland, Ohio, Rhode Island, and Wisconsin.[57] The steel (6.5 lb.) cylinders are then sent to refrigerant manufacturers located in Kentucky, Louisiana, New Jersey, and Texas, who fill them with ODS and/or high-GWP refrigerants.[58] Figure III-1 depicts the locations of both cylinder and refrigerant manufacturers in the United States.

Figure III-1: Locations of Refrigerant and Cylinder Manufacturers in the United States

Blue dots represent refrigerant manufacturing facilities (KY, LA, NJ, TX);
red triangles represent cylinder manufacturing facilities (Il, IN, KY, MD, OH, RI, WI).

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[56] Based on 2004 data from the SAE Improved Mobile Air Conditioning [I-MAC] Research Program.

[57] The primary manufacturers of disposable and refillable cylinders include Worthington, Amtrol, and Manchester. Facility locations listed on company websites: http://www.amtrol.com/, http://www.worthingtoncylinders.com/, http://www.mantank.com/. Some disposable cylinders are also manufactured and filled internationally, and then shipped to California for use. However, for simplicity, this analysis focuses solely on U.S. manufactured cylinders.

[58] Most cylinders are filled by refrigerant manufacturers, although a small number are filled by refrigerant reclaimers. Leading refrigerant manufacturers include Honeywell, DuPont, Arkema, Solvay, and Mexichem Fluor (formerly Ineos Fluor), with facilities in Louisiana, Texas, Kentucky, and New Jersey. There are 3 EPA certified reclaimers in California.

After filling, cylinders are sent to one of the 227 refrigerant distributors within California (HARDI 2009), who then sell them to the approximately 13,000 contractors located throughout the state, who employ up to 60,000 technicians.[59] Once deemed "empty," cylinders are typically evacuated and then sent to a landfill or scrap metal recycling facility. Before cylinders are landfilled or recycled, they must be punctured to release any remaining refrigerant (US AC Distributors 2009). Any cylinder received by a landfill that has not been punctured is either punctured on-site or returned to the point of origin. Cylinders deemed "empty" contain approximately 3.7% or 1.1 lbs. of refrigerant (see Appendix A: Review of Cylinder Evacuation Times, Vacuum Pressures, and Refrigerant Heels). Release of this refrigerant heel could result in 0.03 $MTCO_2eq$ per cylinder containing R-410A refrigerant.

The Air-Conditioning, Heating, and Refrigeration Institute (AHRI) Guideline Q (2010), titled "2010 Guideline for Content Recovery & Proper Recycling of Refrigerant Cylinders", recommends evacuating refrigerant from non-refillable cylinders to a vacuum of 15 inches of mercury, relative to standard atmospheric pressure of 29.9 inches of mercury. And, as of January 1, 2011, the California ARB December 2009 Stationary Refrigeration Equipment Management Rule requires evacuation of cylinders down to this level. Technicians adhere to these mandates guidelines by performing refrigerant evacuation themselves, or by bringing the "empty" cylinder to take-back companies. Typically, once the cylinder heel is evacuated, the recovered refrigerant is collected and stored with other used refrigerant (recovered from service jobs and other routine maintenance activities). When significant quantities are collected, this recovered refrigerant is sent to a reclamation or destruction facility, while the empty metal cylinders are sent to landfills or metal recyclers. In the state of California, there are an estimated 370 landfills. The number of metal recyclers is not known, but believed to be on the order of 100.

The common fate of the metals from scrapped disposable cylinders is highly uncertain, with industry estimates for reuse of recovered metal in the secondary metals market ranging from as low as 15% to nearly 100%. Although many industry representatives claim high levels of cylinder recycling (HARDI 2009, Hudson 2009), others explain that, because of the unstable market for recycled metals and the fact that recycling of cylinders is only profitable if a significant volume is collected—which is uncommon—only 15-20% of cylinders are recycled (Airgas 2009, Berkan 2009). The Steel Recycling Institute estimated that in 2008 (the most recent data available), 65.2% of steel containers (all types, including compressed gas cylinders) were properly recycled (Steel Recycling Institute 2008). Due to the wide range of recycling estimates, and statements by multiple stakeholders that the majority of cylinders get recycled (US AC Distributors 2009; RSD 2009), this analysis conservatively assumes that approximately 75% of cylinders are eventually recycled.

In defining the business-as-usual (BAU) scenario for this analysis, the following assumptions are applied:

- An estimated 732,350 disposable refrigerant cylinders are sold each year in California from 2011 through 2050;[60] of these, 1/6 (122,100 cylinders) contain HFC-134a for use in the automotive sector, and 5/6 (610,300 cylinders) contain HCFC-22 for use in the stationary refrigeration/AC sector. Due to the HCFC phase-out, cylinder sales in the stationary sector

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[59] This analysis only uses the 60,000 figure as a ballpark to estimate distances between technicians and distributors. The number and size of trucks are not affected by the number of technicians.

[60] Due to great uncertainty in the refrigeration/AC market and the potential long-term transition to low-GWP refrigerants, no market growth assumptions are applied.

are assumed to linearly transition from HCFC-22 to R-410A from 2010 to 2020.[61] In practice, other higher-GWP refrigerants, such as R-404A, are also likely to be used.

- Annual sale of refillable 30-lb cylinders in California is negligible (i.e., less than 1% of 30-lb cylinder sales).
- As of January 1, 2011, the average refrigerant heel in 30-lb cylinders in California is 0.17% (0.05 lbs.), assuming full compliance with CARB's evacuation requirements (down to a 15-inch vacuum).[62] See Appendix A: Review of Cylinder Evacuation Times, Vacuum Pressures, and Refrigerant Heels for a more complete discussion of refrigerant heels and evacuation times.
- 80% of disposable cylinders are evacuated by technicians and then sent to landfills or metal recyclers;
- 20% of disposable cylinders are evacuated by cylinder take-back companies and then sent to landfills or metal recyclers;
- 75% of disposable cylinders are eventually recycled at end-of-life (EOL), while the remaining 25% are shredded and landfilled, or stored indefinitely (e.g., in warehouses and garages);
- The distance of each trip in the cylinder pathway is estimated as follows:[63]
    - Cylinder manufacturer to refrigerant manufacturer: 500 miles
    - Refrigerant manufacturer to distributor: 2,500 miles
    - Distributor to technician: 25 miles
    - Technician to take-back company: 25 miles
    - Technician/take-back company to landfill/recycler: 50 miles.
- Figure III-2 graphically presents the BAU pathway for 30-lb. disposable refrigerant cylinders.

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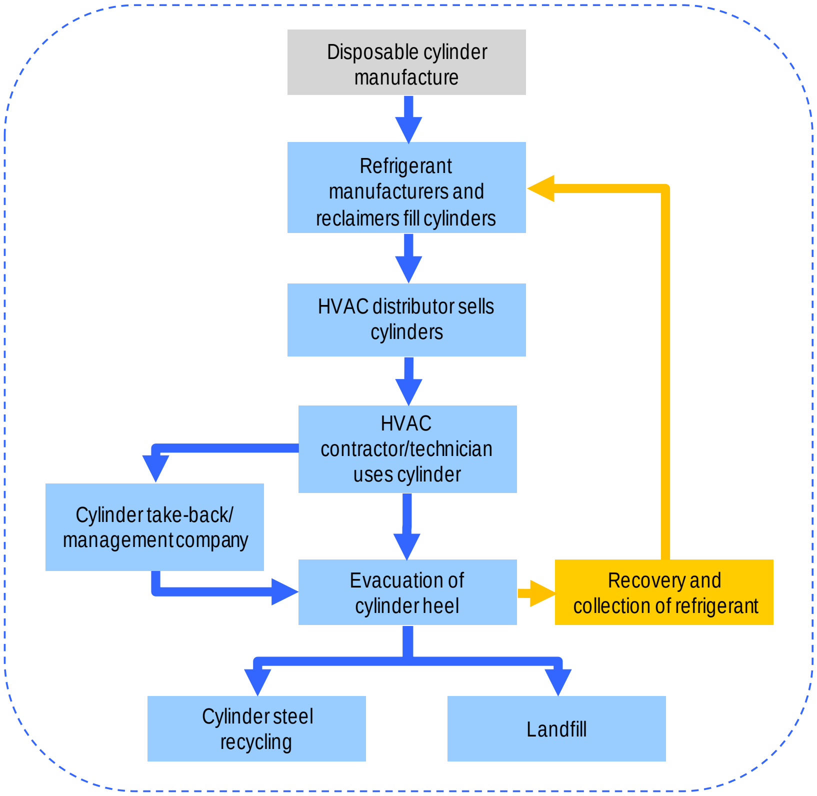
[61] Per the Clean Air Act regulations, the production and import of HCFC-22 is prohibited beginning January 1, 2010, except for use in equipment manufactured before 1/1/2010; beginning January 1, 2020, production and import of HCFC-22 for use in equipment manufactured before 1/1/2010 is prohibited.

[62] Prior to implementation of CARB's Stationary Refrigeration Equipment Management Rule, the average heel is estimated at 3.7%. Additional outreach/education may be needed to actually achieve a heel of only 0,05 lbs, as assumed in the BAU.

[63] Actual distances may vary widely, but simplifying assumptions were necessary for calculation purposes. See Section III.4 for additional detail regarding these assumptions.

Figure III-2: Fate of Disposable Cylinders under Business as Usual (BAU)



Emissions and costs associated with cylinder manufacture, transport, evacuation, and recycling are considered within the boundary of this analysis. The environmental benefits associated with the avoided venting of refrigerant heels are quantified in this analysis, but the carbon footprint and cost associated with any transport and subsequent reclamation of those heels are not. This is because it is assumed that refrigerant heels recovered from cylinders will be used by technicians or sent by take-back companies to reclamation facilities for eventual resale.[64] The emissions associated with any transport of recovered heels from take-back companies to reclamation facilities in the BAU is not expected to be significant, nor are those associated with energy consumption from the reclamation process; moreover, the quantification of such emissions, however small, would only result in a net increase in environmental benefits in the management scenario, since any reclamation of refrigerant heels in the management scenario would occur at the refrigerant manufacturing facilities, and transport to such facilities is quantified in this analysis. Furthermore, the costs associated with any transport/reclamation of cylinder heels in the baseline are also not believed to be significant, and are in fact likely to result in net *negative* costs—since customers are typically *paid* by reclaimers for the return of refrigerant that is clean and has a high market value.[65]

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[64] It is assumed that all cylinder heels will be recovered into a refrigerant holding tank dedicated to a single refrigerant type, such that the recovered heels would be clean/uncontaminated and ready for use; there would therefore be no need to send recovered heels for destruction.

[65] Most HFCs have high market values, and the market value of HCFC-22 is expected to increase steadily beyond 2010 (as virgin HCFC-22 production will be limited for use in existing refrigeration/air conditioning equipment and eventually phased out, which will effectively lead to an increase in demand for reclaimed HCFC-22 as supplies become scarce).

III.3. Description of Alternative Management Scenario

To compare the cost-benefits of disposable and refillable cylinder use, this analysis considers the replacement of disposable cylinders with refillable cylinders over a 5-year phase-in period. This shift to refillables could potentially reduce heel emissions from disposable cylinders and other GHG emissions associated with new cylinder manufacturing. Many countries, including Australia, Canada, and European Union (EU) Member States, among others, have successfully implemented similar programs. The text box (right) summarizes the experiences in Australia and the UK.

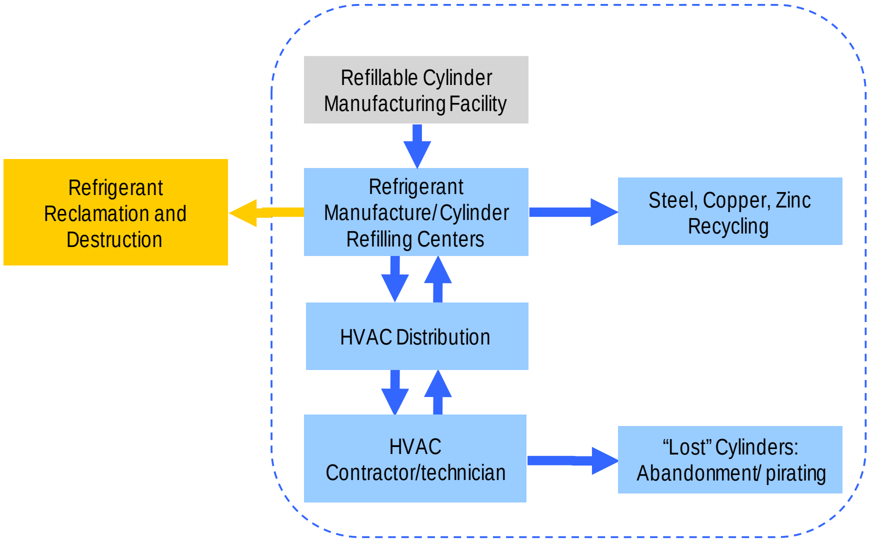
Under this alternative management scenario, cylinder heel emissions would be reduced through the use of refillable cylinders, which are returned to the refrigerant manufacturer for evacuation and reuse or recycling. Specifically, once the refrigerant in a refillable cylinder is used up, technicians would send cylinders back to refrigerant manufacturers via distributors. Refrigerant manufacturers would evacuate, clean, and refill the cylinders for resale. Any refillable cylinders reaching EOL (i.e., those that cannot be properly refurbished and re-circulated) would be evacuated before being sent to a metal recycler. Figure III-3 depicts the cylinder chain of custody assumed in this alternative management scenario.

Disposable Cylinder Bans in Australia and the United Kingdom

The importation of disposable cylinders was banned in Australia in 2000, roughly 18 months after a final rule was promulgated. The Australian market is significantly smaller than that of California. Therefore, the relatively brief phase-in period in Australia may not be feasible in California. In Australia, each refillable cylinder is refilled approximately 1.3 times per year. Approximately 6-10% of cylinders are “lost” annually due to pirating, theft, or damage. Prior to the disposable cylinder ban, cylinder scrapping in Australia was estimated to result in heel emissions of approximately 0.55-0.66 lb./cylinder. (A-Gas Australia 2009)

Disposable HFC cylinders were banned in the UK in 2007. HCFC disposable cylinders were banned several years earlier. In each case, industry was given at least a year to phase-out disposables. According to a UK refrigerant supplier, some refillable cylinders are refilled as many as 3 or 4 times per year. In the UK, a rental fee of about £3/month in addition to the deposit of between £20-30 per cylinder ensures that the cylinders are returned promptly. (A-Gas UK 2009)

Figure III-3: Annual Pathway Management Scenario—Refillable Cylinders



Distances to transport refillable cylinders from cylinder manufacture to refrigerant manufacture, to distributor, to technician, are assumed to be the same as those of disposable cylinders. However, due to the increased size/weight of refillable versus disposable cylinders (described in Section III.4.2), over 30% more truck trips are assumed to be required to transport them.[66] In addition, it is assumed that refillable cylinders are returned to refrigerant manufacturers after use via a producer responsibility scheme, which results in greater transport than in the disposable cylinder scenario.

If refillable cylinders were to replace the use of disposables, a greater number of reusable cylinders would need to be produced (relative to those currently needed on an annual basis) in order to avoid market disruptions and to account for cylinders in transit or in use. Indeed, based on conversations with various stakeholders including HARDI (2009) and National Refrigerants Inc., this analysis estimates that for every disposable cylinder sold, four refillable cylinders must be in circulation to account for cylinders in use and in transit.[67] The actual number of reusable cylinders that must be manufactured would depend on the rate of cylinder return. In Australia, refillable cylinders are refilled approximately 1.3 times per year (A-Gas Australia 2009), whereas refillable cylinders in the UK are refilled as often as 3 or 4 times per year (A-Gas UK 2009). The rate of cylinder return can be increased using financial incentives; for example, in the United Kingdom, a rental fee of roughly £3/month is placed on each reusable cylinder (in addition to a deposit of £20-£30 per cylinder) (A-Gas UK 2009). For additional discussion on how a deposit/refund scheme or rental fees for cylinders could be applied in California, see Appendix B: Deposit/Refund Scheme and Rental Fee for Cylinders.

This analysis assumes that each refillable cylinder is returned once per year. Thus, the total "fleet" of refillable cylinders must be four times the annual disposable cylinder demand.[68] Thus, the total fleet size of refillable cylinders by the end of the phase-in period is assumed to be approximately 2,929,400. Table III-1 presents the assumed number of refillable and disposable cylinders that would need to be manufactured each year, and the resulting fleet size. The transition from disposable to refillable cylinders is assumed to be completed gradually within the 5-year phase-in period (i.e., 20% of disposable cylinder manufacturing is assumed to be replaced by refillables in each of the first five years).

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[66] As explained in Section III.4.3, each truckload is assumed to be capable of transporting approximately 1,120 disposable cylinders or 870 refillable cylinders.

[67] According to National Refrigerants Inc., for each disposable cylinder replaced: one refillable cylinder is needed for the contractor, one for the wholesaler (to keep in stock to give the contractor upon return of an empty cylinder), one is in transit (back to the manufacturer for maintenance and refill), and one is filled in the manufacturer's inventory (to replace the empty one in transit).

[68] Although the refillable cylinder fleet is assumed to be four times the annual market demand, only those that will be sold to technicians in a given year (i.e., 732,350) are assumed to be transported from refrigerant manufacturer to distributor, to technician.

Table III-1: Number of Disposable and Refillable Cylinders Manufactured per Year

Year	Cylinders Manufactured per Year Assuming 5 year Phase out of Disposables			Total Stock of Refillable Cylinders
	Refillable	Disposable	Total	Refillable
2010	585,880	585,880	1,171,760	585,880
2011	615,174	439,410	1,054,584	1,171,760
2012	644,468	292,940	937,408	1,757,640
2013	673,762	146,470	820,232	2,343,520
2014	703,056	0	703,056	2,929,400
2015	146,470	0	146,470	2,929,400
2016	146,470	0	146,470	2,929,400
2017	146,470	0	146,470	2,929,400
2018	146,470	0	146,470	2,929,400
2019	146,470	0	146,470	2,929,400
2020	146,470	0	146,470	2,929,400
Total	**4,101,160**	**1,464,700**	**5,565,860**	**NA**

Refillable cylinders have 10-year test dates—meaning that their integrity is tested every 10 years. Most refillable cylinders last at least 20 years. To be conservative and account for any damaged cylinders, this analysis assumes that 5% of the refillable cylinder fleet reaches EOL annually, and is consequently recycled (Airgas 2009). Therefore, 5% of the total refillable cylinder fleet must be newly manufactured each year to sustain market demand once the phase-in is complete. The manufacture of one refillable cylinder displaces the manufacture of 5 disposable cylinders over the course of its 20-year life. Finally, each refillable cylinder is assumed to be refurbished every 5 years, which would entail inspection, hydrotesting, cleaning, repainting, and possible revalving. Therefore, each year, 3/20 (15%) of the fleet will incur refurbishment costs.

III.4. Key Assumptions

Emissions are calculated based on the IPCC Second Assessment Report (SAR) GWPs for HCFC-22, R-410A, and HFC-134a of 1,500, 1,725, and 1,300, respectively.[69] Impacts on the stratospheric ozone layer are also calculated, based on the 0.055 ozone depletion potential (ODP) of HCFC-22.

III.4.1. Heel Emission Estimates

It is estimated that prior to the implementation of CARB's Stationary Refrigeration Equipment Management Rule, the average refrigerant heel remaining after cylinder use was between 1.85% and 6% (0.56 lbs to 1.80 lbs per cylinder), with a weighted average of 3.7% (1.1 lbs.) (see Appendix A: Review of Cylinder Evacuation Times, Vacuum Pressures, and Refrigerant Heels for further explanation). However, as of January 1, 2011, it is assumed that all disposable

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[69] For consistency with the method used to calculate California's GHG baseline emissions for AB 32, the Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report is used as the source of GWP values. Where GWP values had not yet been calculated for specific refrigerants, the values from the IPCC Third Assessment Report are used.

and refillable cylinders are evacuated at EOL down to a 15-inch vacuum, or 0.05 lbs. refrigerant, per ARB mandate. Incremental upstream fuel cycle emissions associated with the electricity consumed during refrigerant evacuation are de minimus (estimated at roughly 100 $MTCO_2eq$ annually).[70] Full compliance with the Stationary Refrigeration Equipment Management Rule is assumed in this analysis—although it should be underscored that actual compliance levels are highly uncertain and difficult to enforce.

III.4.2. Cylinder Manufacturing/Recycling

An empty new disposable cylinder weighs approximately 6-7 lbs., whereas an empty new refillable cylinder weighs approximately 18 lbs. (Airgas 2009, Hudson 2009). Each cylinder is composed almost entirely of steel. Other components include gaskets and valves, which are a mix of steel and plastic in disposable cylinders, but all brass (a combination of steel and copper) in refillable cylinders. All cylinders are painted. Table III-2 presents the relative percentages by weight of these materials.

Table III-2: Component Weight Percents for Disposable and Refillable Cylinders

Component	Disposable Cylinders	Refillable Cylinders
Steel	98%	90.9%
Copper	0%	7%
Zinc	0%	2%
Paint	0.5%	0.2%
Rubber	0.1%	0.03%
Plastic	1.4%	0%

The differences in weight and composition of disposable versus refillable cylinders lead to different emission profiles associated with material and cylinder manufacturing. Based on GREET 2.7, the lifecycle emission factors of each material component are shown in Table III-3. It should be noted that criteria air pollutant emission factors reflect global emission estimates; due to analytical limitations, emissions for criteria air pollutants could not be disaggregated for California specific regions or air districts.

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[70] Estimate is based on an emission factor from GREET 1.8c of 0.5 kWh/kg refrigerant for compression energy, 708 g CO_2/kWh for power plants, and 46 g CO_2/kWh for the upstream fuel cycle.

Table III-3: Cylinder Component Emission Factors, Based on GREET 2.7[a]

Virgin Material	g CO_2eq / lb[b]	g NO_x / lb[c]	g PM10 / lb[c]	g PM2.5 / lb[c]	g SO_x / lb[c]
Steel	1,117	1.23	0.97	0.29	1.70
Copper	3,909	4.94	3.77	1.44	97.80
Zinc	4,022	5.82	2.43	1.28	5.86
Rubber	1,469	2.10	0.50	0.31	2.05
Plastic	2,180	3.00	1.48	0.60	4.13
Paint[d]	2,000	0.00	0.00	0.00	0.00

[a] Emission factors reflect virgin material manufacture. Calculations of emissions associated with recycled materials manufacturing are based on scaled down emission factors. For steel, the recycled material emission factor is assumed to be 60% of the virgin emission factor; for copper and zinc, it is assumed to be 25%.
[b] CO_2eq emissions capture net CO_2 (from CO_2, VOC, and CO), CH_4, and N_2O.
[c] Additional significant figures are shown to allow for repeat of calculations.
[d] GREET 2.7 does not provide an emission factor for paint. The emission factors used in this analysis are assumptions.

Table III-4 presents the emission factors associated with cylinder fabrication—i.e., steel casting and zinc and copper processing—based on average U.S. electricity and natural gas emission factors reported in GREET 1.8c, and average U.S. natural gas and electricity input rates by material based on EPA (2009) and DOE (2003).[71] Use of U.S. average emission factors is appropriate (in lieu of California specific emission factors) given that steel casting and zinc/copper processing occur throughout the country.

Table III-4: Cylinder Fabrication Emission Factors, Based on GREET 1.8c

Virgin Material	g CO_2eq / lb[a]	g NO_x / lb[b]	g PM10 / lb[b]	g PM2.5 / lb[b]	g SO_x / lb[b]
Steel Casting	626	0.94	0.82	0.22	2.09
Zinc and Copper Processing	826	0.86	0.64	0.17	1.66

[a] CO_2eq emissions capture net CO_2 (from CO_2, VOC, and CO), CH_4, and N_2O.
[b] Additional significant figures are shown to allow for repeat of the calculations.

Based on these emissions factors and those presented in Table III-3, Table III-5 presents the GHG emissions associated with the manufacture and recycling of one disposable cylinder and one refillable cylinder.

Table III-5: Per Cylinder GHG Emissions Associated with Manufacturing and Recycling

GHG Emissions/ Emission Credits	Cylinder Type		Scenario Assumptions
	Disposable	Refillable	
Manufacturing Emissions (kg CO_2eq)	9.67	28.98	• In BAU, ~732,000 disposable cylinders are manufactured annually. • In alternative management scenario, once the refillable fleet is mature (i.e., in 2015), ~146,000 refillable cylinders are manufactured annually.
Recycling Emission Credits (kg CO_2eq)[a]	1.14	4.81	• In BAU, 75% of disposable cylinders sold annually reach EOL and are recycled. • In alternative management scenario, 5% of refillable cylinder fleet reaches EOL each year and is recycled.

[a] Emission credits due to recycling reflect the lower quantity of virgin materials that must be produced.

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[71] Emission factors for steel casting were developed using an electricity input rate of 6.03 MMBtu/MT; emission factors for zinc and copper processing were calculated assuming energy input rates of 2,102 Btu/lb for electricity and 4,954 Btu/lb for natural gas.

III.4.3. Transportation

Table III-6 presents the average travel distances assumed for disposable and refillable cylinders in this analysis. Average distances were roughly estimated based on the relative number and location of entities performing the relevant services.

Table III-6: Assumed Distances Between Entities in the (Disposable and Refillable) Cylinder Pathway

Step in Pathway		Distance (miles)	
		BAU: Disposables	Alternative: Refillables
A	Cylinder manufacturer to refrigerant manufacturer	500	500
B	Refrigerant manufacturer to distributor	2,500	2,500
B2	Truck return trip, back to refrigerant manufacturers from distributors	0	2,500[a] (return of used cylinders)
C	Distributor to technician	25	25
C2	Truck return trip, back to distributor from technician	0	25 (return of used cylinders)
D	Technician to take-back company	25	NA
E	Technician/take-back company to landfill or recycling facility	50	NA
F	Refrigerant manufacturer to recycling facility	NA	50

[a] Actual distance to transport reusable cylinders for refilling may be much lower if refilling facilities are established in California, which is not assumed in this analysis.

In the BAU, new cylinders travel from cylinder manufacturer to technician via steps A through C, and then are (a) returned to a take-back company and then a landfill/recycling facility (steps D and E) or (b) sent directly to a landfill/recycling facility (step E). In addition, it is assumed that all vehicles that transport cylinders to one location will travel back from that location with a different load; therefore, return trips in the BAU are not included in this analysis.

Under the alternative management scenario where refillable cylinders replace disposables, new cylinders also travel from cylinder manufacturer to technician via steps A through C, but are then returned to the refrigerant manufacturer via their original distribution pathway (i.e., B2 and C2).[72] Once returned to the refrigerant manufacturer, used cylinders are either refilled for resale (steps B and C), or sent to a recycler (step F) if they've reached end-of-life. It is assumed that after delivering new cylinders to refrigerant manufacturers and after delivering evacuated cylinders to recycling facilities, trucks will return carrying other goods and are therefore not included in the analysis.

Based on the distances specified in Table III-6, annual transport requirements per cylinder in the BAU and alternative management scenario are as follows:[73]

- *BAU*: 3,075 per cylinder handled by technicians; 3,100 miles per cylinder handled by take-back company.

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[72] Actual distance to transport reusable cylinders for refilling may be much lower if refilling facilities are established in California.

[73] Total annual distance for the full cylinder fleet is calculated based on these assumptions, in addition to the fate of each cylinder at end of life and the number of trucks required to transport them (which is in turn dependent on the weight of the cylinders and, in regulatory scenarios, the number of additional trips required).

- *Alternative Management Scenario*: 5,550 miles if cylinder is newly manufactured, used, and refilled (i.e., re-enters the fleet); 5,050 miles if used cylinder is re-circulated for use and then refilled for fleet re-entry; 5,100 miles if used cylinder is re-circulated for use and then reaches EOL.

Cylinders are transported in heavy-duty 53-foot trucks whose capacity is limited by weight. Each truckload is assumed to be capable of transporting approximately 1,120 disposable cylinders or 870 refillable cylinders.[74] The lighter the cargo load, the better the gas mileage; therefore, a truck transporting empty cylinders is estimated to achieve gas mileage of approximately 7 or 8 miles per gallon (mpg) compared to 4 or 5 mpg for a truck with maximum cargo load. Table III-7 presents the varying cargo loads based on type of cylinders and quantities of refrigerant in the transported cylinders.

Table III-7: Cargo Weight per Truckload

Load	Disposable Cylinders (lbs.)	Refillable Cylinders (lbs.)
Empty cylinders[a]	8,400	16,500
Used cylinders[b]	9,700	17,500
Full cylinders	42,000	42,600

[a] The transport of empty cylinders is assumed to occur when newly manufactured cylinders are sent to refrigerant producers for filling, as well as when evacuated/punctured cylinders are sent to landfills/recyclers.
[b] Used cylinders are assumed to contain a heel of approximately 1.1 lbs.

Based on assumed distances between each entity in the cylinder management pathway and cargo weights per truckload, Table III-8 presents the average distance traveled per cylinder in each scenario, as well as the total average distances traveled annually for the production/management of cylinders by scenario.

Table III-8: Average Annual Distance Traveled by Scenario (miles)

Scenario	Average Distance Traveled per Cylinder	Annual Transport Requirements for Cylinder Fleet
BAU: Disposables	3,080	2,013,960
Alternative: Refillables	5,100[a]	4,292,450[b]

[a] The average distance traveled is based on the various pathways for refillable cylinders only (not the disposable cylinders being phased out).
[b] Average distances vary by year; values shown here are for post-2015, once the refillable cylinder fleet is assumed to reach maturity.

The resulting emissions assumed per mile are presented in Table III-9. Diesel fuel is assumed to have a lower heating value (LHV) of 135.5 MJ/gal and a CO_2eq emission factor of 94.7 g CO_2eq/MJ, based on GREET 1.8b used for the California Low Carbon Fuel Standard (ARB 2009b).[75]

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[74] Cylinders are transported on pallets (approximately 40 cylinders per pallet) in large trucks with an estimated capacity of 42,000-45,000 lbs. Approximately 33,600 lbs. of refrigerant in 1,120 disposable cylinders (28 pallets) will fit in one truckload (Hudson 2009). According to Hudson (2009), because refillable cylinders are heavier, only 25,000 lbs. of refrigerant (about 25% less than in refillable cylinders) in 840 refillable cylinders (21 pallets) is transported in a singled truckload. Due to varying industry estimates, however, it is assumed that 870 refillable cylinders are transported per truckload.

[75] The CO_2eq emission factor for diesel fuel includes well to tank (WTT) and tank-to-wheel energy and greenhouse gas values and vehicle fuel emissions for California Ultra Low-Sulfur Diesel (ULSD).

Table III-9: Emissions per Mile (kgCO_2eq/mile) Based on Varying Cargo Loads

Load	Emissions per mile (kgCO_2eq/mile)	
	Disposable Cylinders	Refillable Cylinders
Empty cylinders	1.73	1.94
Used cylinders	1.77	1.97
Full cylinders	2.67	2.67

Criteria pollutant emissions associated with transport are based on the emission factors presented in Table III-10, based on Façanha and Horvath (2007). As explained above, criteria air pollutant emission factors reflect global emission estimates, as they could not be disaggregated for California specific regions or air districts.

Table III-10: Criteria Pollutant Transport Emission Factors (g/mile)[a]

Load	Disposables				Refillables			
	NO_x	PM10	PM2.5	SO_x	NO_x	PM10	PM2.5	SO_x
Empty cylinders[b]	10.15	0.28	0.05	0.26	19.97	0.55	0.10	0.51
Used cylinders[c]	11.72	0.32	0.06	0.30	21.19	0.58	0.11	0.54
Full cylinders	50.73	1.40	0.26	1.29	51.49	1.42	0.26	1.31

[a] Emission factors account for fuel combustion and pre-combustion.
[b] The transport of empty cylinders is assumed to occur when newly manufactured cylinders are sent to refrigerant producers for filling, as well as when evacuated and punctured cylinders are sent to landfills or recyclers.
[c] Used, unevacuated cylinders are assumed to contain a 3.7% heel.

Source: Façanha and Horvath (2007).

If disposable cylinders were banned in California, the cost to refill the cylinders out of state may be high enough to warrant the construction of new refilling facilities in California. Access to in-state facilities would significantly decrease the distance that empty cylinders would need to travel before being refilled. Although beyond the scope of this analysis, the resulting costs and emissions would most likely be even lower for this scenario than those presented here.

It is important to note that emissions and costs associated with the transport of raw steel (and other materials) *from the steel manufacturing facilities* to cylinder manufacturing plants are not included in this analysis because they are not within the scope of the research. However, because the annual amount of steel needed for the manufacture of disposable cylinders is up to 3 times greater than that required for refillable cylinders, this transport of raw materials could be significant. Therefore, the lifecycle cost of using only refillable cylinders is lower than that shown in this analysis.

III.4.4. Associated Costs

Costs in the BAU and refillables scenario are based on cylinder manufacture/recycling, transport fuel, and labor associated with truck driving and refrigerant evacuation, as outlined below.[76]

- Manufacturing costs of disposable and refillable cylinders are estimated at $8.50 and $47.50 per cylinder, respectively (Hudson 2009, Airgas 2009).[77]
- Metal on the recycling market is assumed to be valued at $100/ton, such that the estimated benefit from recycling cylinders is approximately $0.33 per disposable cylinder and $0.90 per refillable cylinder (SA Recycling 2009). This value is subtracted from the total manufacturing costs, as appropriate (i.e., based on the assumed level of recycling in each scenario).
- Diesel fuel costs approximately $2.54 per gallon (EIA 2009a).
- Average truck highway speed is 50 mph (Façanha and Horvath 2007).
- Cylinder evacuation costs are estimated based on an assumed labor rate of $40/hour, and an assumed evacuation time of 2 minutes per cylinder for small-scale establishments (e.g., distributors or take-back companies), and 1 minute per cylinder for larger establishments (e.g., refrigerant manufacturers and refillers) (ARB 2008, 2009; Berkan 2009; Airgas 2010). Actual evacuation time will depend on many factors, including the type of refrigerant, ambient temperature, vapor and liquid content in the cylinder, the size of equipment and piping/tubing used for evacuation, and inefficiencies in the evacuation procedure.
- Electricity costs associated with refrigerant evacuation are de minimus.
- Basic refrigerant recovery equipment, including a simple recovery device, vacuum pump, liquid pump and scale, is estimated to cost approximately $12,000, while refrigerant evacuation/refilling equipment is estimated to cost $32,000 (Hudson 2009b, Airgas 2009b). However, it is assumed that no additional equipment is required under the refillable cylinder scenario, given that all cylinders will be returned to refrigerant manufacturers who already own the necessary refrigerant recovery and/or refilling equipment.
- Cost of refurbishing refillable cylinders every five years throughout their 20-year lifetime is assumed to be $13/cylinder, based on communication with Dupont (2011) and Airgas (2011). This cost reflects any repainting, cleaning, inspection, hydrotesting, or revalving that must be conducted.
- The cost associated with manufacturing set-up time is considered to be negligible and is not quantified in this analysis.

An annual discount rate of 5% is applied to both management scenarios. This discount rate was chosen for consistency with other ARB analyses.

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[76] This analysis assumes that manufacturers will reclaim or reuse the evacuated refrigerant heel. Consequently, no costs are associated with destroying the cylinder heels.

[77] In addition to the cost associated with producing disposable versus refillable cylinders, the number of cylinders that must be produced in each scenario also affects costs. In particular, for refillable cylinders, a greater number must be manufactured in the early years (prior to 2015) as the fleet is being built up, but a significantly lower number must be produced thereafter (since refillable cylinders need only be replaced every 10-20 years, as opposed to every year for disposable cylinders).

III.4.5. Storage and Handling

In the refillable cylinder scenario, it is assumed that cylinders are returned to the refrigerant manufacturer for refilling. To minimize transport costs, distributors would likely store used cylinders until they had accumulated full truckloads to transport back to the refrigerant manufacturers. According to refrigerant distributors in California, some distributors may not have sufficient storage capacity to handle the larger refillable cylinder fleet size or any used refillable cylinders that will be sent back to refrigerant manufacturers (RSD 2009; US AC Distributors 2009). These distributors may need to rent additional warehouse space. Others may have sufficient space and will therefore incur no additional costs. The amount of additional storage space that may be needed is highly uncertain, and is not included in this analysis.

III.4.6. Health and Safety

The additional weight of refillable cylinders (which totals 48 lbs. when full) could potentially cause worker safety issues under certain conditions (e.g., based on frequency of lift, lift duration, etc.). Although this is unlikely, workers and employers should consult the National Institute for Occupational Safety and Health (NIOSH) “lifting equation,”[78] which allows for the calculation of a recommended weight for a variety of lifting tasks, to prevent work-related low back pain and disability. NIOSH also provides an approach for controlling the hazards of low back injury from manual lifting.

Costs associated with safety concerns are not included in this analysis. However, workers carrying heavier cylinders may have reduced efficiency due to the load. In some cases, additional technicians may be required. In addition, potential injuries from carrying a heavier load could result in additional medical costs. These undetermined potential costs are highly uncertain, and insufficient data exist to include them in the quantitative analysis of the refillable cylinder scenario.

III.5. Cost Assessment

III.5.1. BAU

Costs in the BAU are calculated based on estimated costs of cylinder manufacture, value for metal recycling, diesel fuel prices, and an assumed labor rate of $40/hour, as described in Section III.4.4. Total labor costs include both cylinder evacuation (two minutes/cylinder) and truck transport (average truck speed 50 mph). Assumed annual costs in the BAU are shown in Table III-11.

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[78] The “Applications Manual for the Revised NIOSH Lifting Equation” is available at <http://www.cdc.gov/niosh/docs/94-110/>.

Table III-11: Total Annual Costs in BAU

Costs Source	Assumptions	Annual Costs	Average Cost per Cylinder
Labor: Transport	Labor time required to transport cylinders (speed of 50 mph)	$1,611,170	$2.20
Labor: Evacuation	Labor time required to evacuate cylinders (2 min/cylinder)	$976,467	$1.33
Cylinder Manufacture & Recycling	732,350 cylinders manufactured at $8.50 each minus the value of cylinder recycling	$6,050,035	$8.26
Cylinder Refurbishment	No disposable cylinders will be refurbished	$0	$0.00
Transport	Cost of diesel fuel ($2.54/gallon) at fuel efficiencies shown in Table III-9	$998,272	$1.36
Total		$9,635,944	$13.16

As shown, the total annual cost associated with cylinder manufacture, recycling, transport, and labor is estimated at approximately $9.6 million per year in the BAU. Because the cylinder fleet is assumed to remain constant each year, annual costs in the BAU will remain constant through 2050. Table III-12 presents the NPV costs from 2010-2020 and 2050 in the BAU. Approximately 62% of the total 2010-2020 NPV costs are associated with handling cylinders containing HFC refrigerants; from 2010-2050, these costs represent 82% of the total NPV costs.

Table III-12: Total NPV Costs in BAU

Year	Labor: Transport	Labor: Evacuation	Cylinder Manufacture/ Recycling	Cylinder Refurbishment	Transport Fuel	Total
2010–2020	$14,052,198	$8,516,483	$52,766,801	$0	$8,706,667	$84,042,149
2010–2050	$29,257,375	$17,731,743	$109,863,106	$0	$18,127,715	$174,979,938

III.5.2. Alternative Management Scenario

In the alternative management scenario, incremental costs are incurred due to the additional transport (labor and fuel costs) required for the heavier refillable fleet of 2,929,400 cylinders. Full truckloads of refillable cylinders have lower fuel efficiency than in the BAU (see Table III-9). However, despite the higher cylinder manufacturing costs incurred in the initial years, only 5% of the cylinder fleet is replaced each year (to account for cylinders that reach EOL) once the phase-out of disposable cylinders is complete. Thus, after the initial 5-year phase-in of refillable cylinders, manufacturing costs are significantly reduced. Table III-13 presents the annual costs for this scenario following refillable cylinder phase-in.

Table III-13: Annual Costs in Alternative Management Scenario, Post 5-Year Phase-in of Refillables

Costs Source	Assumptions	Annual Costs	Total Annual Costs per Cylinder in Use
Labor: Transport	Additional transport to accommodate heavier cylinders (250 fewer cylinders per truckload) and cylinder return to refrigerant manufacturer	$3,474,874	$4.74
Labor: Evacuation	All used cylinders are evacuated (1 minute/ cylinder)	$488,233	$0.67
Cylinder Manufacture & Recycling	2,929,400 refillable cylinder fleet, of which 5% is replaced annually; 5% of cylinder fleet recycled, with metal valued at $100/ton	$6,825,805	$9.32
Cylinder Refurbishment	3/20 of fleet is refurbished per year	$5,712,330	$7.80
Transport	Additional fuel costs due to increase in number of truck trips (due to heavier cylinders)	$1,990,958	$2.72
Total		$18,492,201	$25.25

Table III-14 presents the annual NPV costs from 2010-2020 and 2050.

Table III-14: Total Annual Costs in Alternative Management Scenario

Year	Labor: Transport	Labor: Evacuation	Cylinder Manufacture/ Recycling	Cylinder Refurbishment	Transport Fuel	Total
2010	$2,239,813	$878,820	$32,643,024	$1,142,466	$1,319,914	$38,224,036
2015	$3,474,874	$488,233	$6,825,805	$5,712,330	$1,990,958	$18,492,201
2020	$3,474,874	$488,233	$6,825,805	$5,712,330	$1,990,958	$18,492,201
2025	$3,474,874	$488,233	$6,825,805	$5,712,330	$1,990,958	$18,492,201
2030	$3,474,874	$488,233	$6,825,805	$5,712,330	$1,990,958	$18,492,201
2035	$3,474,874	$488,233	$6,825,805	$5,712,330	$1,990,958	$18,492,201
2040	$3,474,874	$488,233	$6,825,805	$5,712,330	$1,990,958	$18,492,201
2045	$3,474,874	$488,233	$6,825,805	$5,712,330	$1,990,958	$18,492,201
2050	$3,474,874	$488,233	$6,825,805	$5,712,330	$1,990,958	$18,492,201
NPV 2010-2020	$27,916,151	$5,189,307	$178,238,553	$38,927,970	$16,031,173	$266,303,153
NPV 2010-2050	$60,709,763	$9,796,936	$242,656,075	$92,837,235	$34,820,542	$440,820,551

The annual costs associated with this management scenario range from $18 million to $45 million, with the higher costs incurred in the initial years (when the fleet of reusable cylinders is being built-up).

III.6. Benefits

Based on the pathways and boundaries established in Sections III.2 and III.3, this section presents the estimated lifecycle impacts on ODS, GHG, and criteria air pollutant emissions in the BAU and cylinder management scenarios. More specifically, in estimating GHG impacts, this assessment estimates the direct emissions associated with refrigerant heel losses, as well as the indirect emissions associated with cylinder manufacture, recycling, and transport.

III.6.1. BAU

Annual emissions associated with refrigerant heels and cylinder manufacture, recycling, and transport are estimated based on the assumptions detailed in Sections III.2 and III.4. Table III-15 presents the total annual direct emissions beginning in 2020 from refrigerant heels, based on the assumption that there is full compliance with California's newly implemented Refrigerant Management Rule such that only 0.05 lbs. of refrigerant will be emitted from each of the 732,350 cylinders used each year. The disposal of each HCFC-22 cylinder results in emissions of 0.0013 ODP kg and 0.034 $MTCO_2eq$; each R-410A cylinder disposed results in 0.039 $MTCO_2eq$; and each HFC-134a cylinder disposed results in 0.030 $MTCO_2eq$. Because it is assumed that R-410A will gradually replace HCFC-22 in the stationary/HVAC sector ODP-weighted emissions will gradually decrease from 0.7 MT to 0.0 MT in the first 10 years (i.e., by 2019). However, annual GHG emissions will rise from 24,724 to 27,532 $MTCO_2eq$ by 2019. It should be underscored that actual compliance with the Refrigerant Management Rule is highly uncertain and difficult to enforce; if the analysis were to assume no compliance with this Rule (i.e., a 3.7% heel per cylinder), baseline emissions would be orders of magnitude higher—approximately 611,200 $MTCO_2eq$ would be emitted each year.

Table III-15: Annual Refrigerant Heel Emissions in BAU (2019-2050)

Refrigerant	Refrigerant Emitted		Ozone Impact	Climate Impact
	lbs.	MT	ODP (MT)	$MTCO_2eq$ Emissions
R-410A	30,515	14	0	23,926
HFC-134a	6,103	3	0	3,606
Total	36.618	17	0	27,532

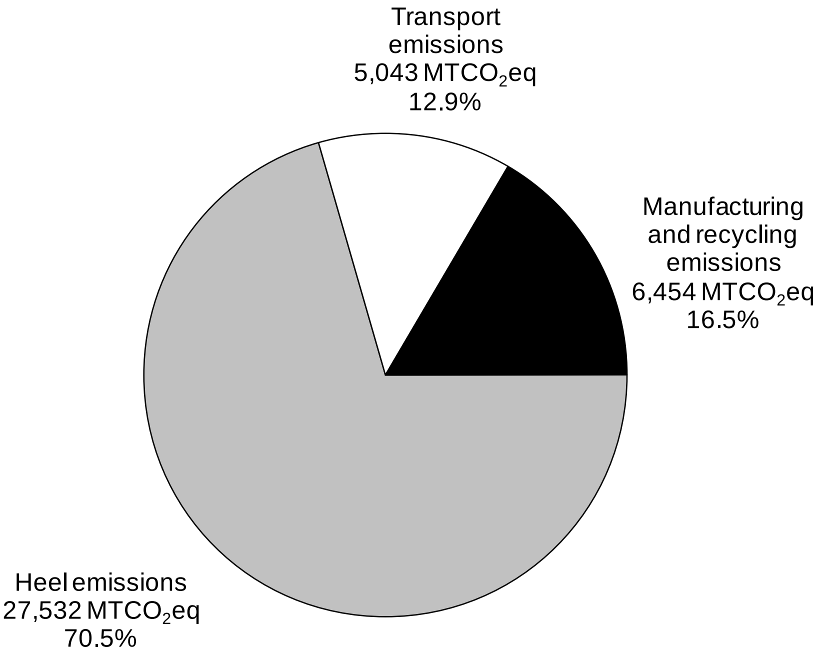
Manufacturing and recycling emissions are presented in Table III-16, based on materials emission factors and total quantity of materials. Emissions associated with manufacturing cylinders are partially offset by the emissions savings resulting from recycling 75% of cylinders at EOL. Transport emissions are also presented in Table III-16, based on total truck miles traveled, cargo load, and a diesel emission factor.

Table III-16: Annual GHG Emissions from Cylinder Manufacture, Recycling and Transport in BAU ($MTCO_2eq$) (2010-2050)

Emissions Source	Annual GHG Emissions ($MTCO_2eq$)	Average Emissions per Cylinder ($MTCO_2eq$)	Assumptions
Transport emissions	5,043	0.007	Transport requirements for annual cylinder fleet is ~2.0 million miles
Manufacturing emissions	7,079	0.010	732,350 cylinders manufactured with 40% virgin steel
Recycling Credits (Negative emissions)	-625	-0.001	75% recycling rate at EOL
Total	11,497	0.016	

Beginning in 2019 (after which point annual climate benefits become constant), total annual GHG emissions associated with BAU practices are estimated at 39,029 $MTCO_2eq$ per year, equivalent to approximately 0.049 $MTCO_2eq$ per cylinder. Heel emissions are estimated to account for approximately 70% of total GHG emissions associated with cylinder EOL management, as depicted in Figure III-4.

Figure III-4: Annual GHG Emissions in BAU (2019-2050)



Criteria Pollutant Emissions

Criteria pollutant emissions result from cylinder manufacturing, recycling, and transport, as shown in Table III-17. Transport accounts for 91% of NO_x, but only 26% of PM10, 19% of PM2.5, and 13% of SO_x emissions. Per cylinder criteria pollutant emissions are approximately 0.13 kg NO_x, 0.013 kg PM10, 0.003 kg PM2.5, and 0.024 kg SO_x.

Table III-17: Annual Criteria Pollutant Emissions (MT) in BAU

		PM10	PM2.5	SO_x
Cylinder Manufacturing	8.99	7.39	2.08	16.05
Cylinder Recycling Credits	-0.69	-0.54	-0.16	-0.95
Transport	87.45	2.41	0.44	2.23
Total	95.75	9.25	2.37	17.33

Net Environmental Impacts

Environmental impacts result from the release of refrigerant heels and the manufacture, transport, and disposal/recycling of disposable cylinders. Until 2019, ODS are emitted when HCFC-22 refrigerant heels are released at time of cylinder disposal. Direct GHG emissions result when HCFC-22, R-410A, and HFC-134a refrigerant heels are released at time of cylinder disposal. Indirect GHG emissions also result from cylinder manufacture, transport, and recycling. The manufacturing, transport, and recycling of cylinders also result in criteria pollutant emissions. Table III-18 summarizes the total ODS, GHG, and criteria pollutant emissions in the BAU from 2010 to 2020 and 2050. As shown, annual emissions are assumed to remain constant beginning in 2020, once the sale of HCFC-22 cylinders is prohibited for servicing refrigeration/AC equipment.

Table III-18: Summary of ODS, GHG, and Criteria Pollutant Emissions in BAU[a]

Year	ODS Emissions (ODP Tons)	GHG Emissions ($MTCO_2eq$)					Criteria Pollutant Emissions (MT)			
	Heel	Heel	Transport	Manufacturing	(Recycling)	Total	NO_x	PM10	PM2.5	SO_x
2010	0.7	24,724	5,043	7,079	-625	36,220	95.7	9.3	2.4	17.3
2015	0.3	26,284	5,043	7,079	-625	37,781	95.7	9.3	2.4	17.3
2020	0.0	27,532	5,043	7,079	-625	39,029	95.7	9.3	2.4	17.3
2025	0.0	27,532	5,043	7,079	-625	39,029	95.7	9.3	2.4	17.3
2030	0.0	27,532	5,043	7,079	-625	39,029	95.7	9.3	2.4	17.3
2035	0.0	27,532	5,043	7,079	-625	39,029	95.7	9.3	2.4	17.3
2040	0.0	27,532	5,043	7,079	-625	39,029	95.7	9.3	2.4	17.3
2045	0.0	27,532	5,043	7,079	-625	39,029	95.7	9.3	2.4	17.3
2050	0.0	27,532	5,043	7,079	-625	39,029	95.7	9.3	2.4	17.3
2010–-2020	3.4	288,814	55,475	77,865	-6,876	415,278	1,053.2	101.8	26.0	190.6
2010–2050	3.4	1,114,788	206,770	290,223	-25,627	1,586,154	3,925.7	379.4	97.1	710.5

[a] Estimates are presented on an annual basis, except where otherwise specified.

III.6.2. Alternative Management Scenario

The alternative management scenario results in reduced ODS/direct GHG emission due to avoided heel losses from disposable cylinders at EOL. Indeed, only those refillable cylinders assumed to reach EOL (5% of fleet per year) are assumed to produce heel emissions. In addition, because it is assumed that R-410A will gradually replace HCFC-22 in the stationary/HVAC sector, ODP-weighted emissions will gradually decrease to zero (by 2019). However, after the phase-in of refillables is complete, annual GHG emissions will rise from 5,194 to 5,506 $MTCO_2eq$ by 2019. Table III-19 presents the annual heel emissions resulting from the use of refillable cylinders from 2019-2050.

Table III-19: Annual Heel Emissions in Alternative Management Scenario (2019-2050)

Refrigerant	Refrigerant Emissions		Climate Impacts ($MTCO_2eq$)
	lbs.	MT	
R-410A	6,103	2.8	4,785
HFC-134a	1,221	0.6	721
Total	7,324	3.3	5,506

Manufacturing, recycling, and transport emissions are presented in Table III-20.

Table III-20: Annual GHG Emissions from Cylinder Manufacture, Recycling and Transport in Alternative Management Scenario ($MTCO_2eq$) (2019-2050)

Emissions Source	Annual GHG Emissions ($MTCO_2eq$)	Average Emissions per Cylinder ($MTCO_2eq$)	Assumptions
Transport emissions	10,058	0.014	Transport requirements for annual cylinder fleet (beyond 2014) are ~4.3 million miles
Manufacturing emissions	4,882	0.007	146,470 cylinders manufactured, 5% annual recycling rate
Recycling Credits (Negative emissions)	-705	-0.001	
Total	13,599	0.019	

Beginning in 2019, total annual GHG emissions associated with the refillables scenario are estimated at 19,105 $MTCO_2eq$ per year, equivalent to approximately 0.026 $MTCO_2eq$ per cylinder. Heel emissions are estimated to account for approximately 29% of GHG total emissions.

Criteria Pollutant Emissions

Criteria pollutant emissions result from cylinder manufacturing, recycling, and transport, as shown in Table III-21. Transport accounts for 95% of NO_x, but only 46% of PM10, 32% of PM2.5, and 20% of SO_x emissions. Per cylinder criteria pollutant emissions are approximately 0.22 kg NO_x, 0.014 kg PM10, 0.002 kg PM2.5, and 0.026 kg SO_x.

Table III-21: Annual Criteria Pollutant Emissions (MT) in Alternative Management Scenario

		PM10	PM2.5	SO_x
Cylinder Manufacturing	8.32	6.58	1.89	21.57
Cylinder Recycling Credits	-0.83	-0.62	-0.21	-6.24
Transport	155.2	4.73	0.79	3.95
Total	162.72	10.23	2.47	19.28

Net Environmental Impacts

Table III-22 summarizes the total ODS, GHG, and criteria pollutant emissions in the refillables scenario from 2010 to 2020 and 2050. As shown, annual emissions are assumed to remain constant beginning in 2019, once the sale of HCFC-22 cylinders is prohibited for servicing refrigeration/AC equipment.

Table III-22: Summary of ODS, GHG, and Criteria Pollutant Emissions in the Alternative Management Scenario[a]

Year	ODS Emissions (ODP Tons)	GHG Emissions (MTCO$_2$eq)					Criteria Pollutant Emissions (MT)			
	Heel	Heel	Transport	Manufacturing	(Recycling)	Total	NO$_x$	PM10	PM2.5	SO$_x$
2010	0.6	20,768	6,668	22,644	-641	49,439	143	31	9	89
2015	0.1	5,257	10,058	4,245	-705	18,856	163	9	2	16
2020	0.0	5,506	10,058	4,245	-705	19,105	163	9	2	16
2025	0.0	5,506	10,058	4,245	-705	19,105	163	9	2	16
2030	0.0	5,506	10,058	4,245	-705	19,105	163	9	2	16
2035	0.0	5,506	10,058	4,245	-705	19,105	163	9	2	16
2040	0.0	5,506	10,058	4,245	-705	19,105	163	9	2	16
2045	0.0	5,506	10,058	4,245	-705	19,105	163	9	2	16
2050	0.0	5,506	10,058	4,245	-705	19,105	163	9	2	16
2010–2020	1.7	97,820	103,719	133,027	-7,593	326,974	1,825	213	56	540
2010–2050	1.7	263,015	405,463	260,388	-28,735	900,132	6,703	495	123	1,035

[a] Estimates are presented on an annual basis, except where otherwise specified.

III.7. Discussion of Findings

This section summarizes the incremental costs and benefits of the refillable scenario relative to the baseline disposable cylinder scenario, as well as the cost-effectiveness in terms of $/MTCO$_2$eq.

III.7.1. Incremental Costs

Incremental costs associated with the refillables scenario are due primarily to increased transportation and related labor costs, as well as manufacture of refillable cylinders, which are significantly more expensive to produce than disposables. Table III-23 presents the per-cylinder incremental costs associated with the alternative management scenario.

Table III-23: Annual Per-Cylinder Incremental Costs for Alternative Management Scenario, Post 5-Year Phase-in of Refillables

Costs Source	Total Annual Incremental Costs per Cylinder
Labor: Transport	$2.54
Labor: Evacuation	-$0.67
Cylinder Manufacture & Recycling	$1.06
Cylinder Refurbishment	$7.80
Transport	$1.36
Total	$12.09

Table III-24 presents incremental costs for the refillables scenario from 2010-2020 and 2010-2050 by source; presents the total incremental costs. During the phase-in of refillable cylinders, higher incremental costs are realized as a large number of reusable cylinders must be manufactured alongside the remaining disposables. Table III-24 presents total annual incremental costs from 2010 through 2020 and through 2050. Net present value (NPV) costs are calculated assuming a discounting rate of 5%.

Table III-24: Incremental Costs ($) for Alternative Management Scenario

Year	Labor: Transport	Labor: Evacuation	Cylinder Manufacture/Recycling	Cylinder Refurbishment	Transport fuel	Total
2010	628,643	(97,647)	26,592,989	1,142,466	321,641	28,588,092
2015	1,863,704	(488,233)	775,770	5,712,330	992,685	8,856,257
2020	1,863,704	(488,233)	775,770	5,712,330	992,685	8,856,257
2025	1,863,704	(488,233)	775,770	5,712,330	992,685	8,856,257
2030	1,863,704	(488,233)	775,770	5,712,330	992,685	8,856,257
2035	1,863,704	(488,233)	775,770	5,712,330	992,685	8,856,257
2040	1,863,704	(488,233)	775,770	5,712,330	992,685	8,856,257
2045	1,863,704	(488,233)	775,770	5,712,330	992,685	8,856,257
2050	1,863,704	(488,233)	775,770	5,712,330	992,685	8,856,257
NPV 2010–2020	13,863,953	(3,327,177)	125,471,752	38,927,970	7,324,506	182,261,004
NPV 2010–2050	31,452,388	(7,934,806)	132,792,969	92,837,235	16,692,827	265,840,613

III.7.2. Incremental Benefits

ODS emissions are avoided in the alternative management scenario until 2019, when all R-22 is assumed to be phased out. Table III-25 presents the incremental ODS emissions avoided for this scenario from 2010-2020.

Table III-25: ODP-Weighted Emissions Avoided in Refillables Scenario

Year	Emissions Avoided (ODP weighted MT)
2010	0.11
2011	0.20
2012	0.26
2013	0.29
2014	0.31
2015	0.24
2016	0.18
2017	0.12
2018	0.06
2019	0.00
2020	0.00
Total	1.77

The alternative management scenario also results in reduced GHG emissions. Under this scenario, it is estimated that over 20 million fewer cylinders would be manufactured by 2050. Table III-26 summarizes total ODS and GHG emissions reductions in the refillables scenario. Table III-27 summarizes the net impact on criteria pollutant emissions.

Table III-26: Total Emissions Avoided in Alternative Management Scenario Relative to BAU[a]

Year	ODS Emissions Avoided (ODP Tons)	GHG Emissions Avoided (MTCO2eq)					Criteria Pollutant Emissions Avoided (MT)			
		Direct	Indirect			Total				
	Heel	Heel	Transport	Manufacturing	Recycling Credits		NO_x	PM10	PM2.5	SO_x
2010	0.1	3,956	(1,625)	(15,566)	16	(13,219)	(47)	(22)	(6)	(71)
2015	0.2	21,027	(5,015)	2,833	80	18,925	(67)	(0)	0	1
2020	0.0	22,026	(5,015)	2,833	80	19,924	(67)	(0)	0	1
2025	0.0	22,026	(5,015)	2,833	80	19,924	(67)	(0)	0	1
2030	0.0	22,026	(5,015)	2,833	80	19,924	(67)	(0)	0	1
2035	0.0	22,026	(5,015)	2,833	80	19,924	(67)	(0)	0	1
2040	0.0	22,026	(5,015)	2,833	80	19,924	(67)	(0)	0	1
2045	0.0	22,026	(5,015)	2,833	80	19,924	(67)	(0)	0	1
2050	0.0	22,026	(5,015)	2,833	80	19,924	(67)	(0)	0	1
2010–2020	1.8	190,994	(48,244)	(55,163)	717	88,304	(771)	(111)	(30)	(350)
2010–2050	1.8	851,773	(198,693)	29,835	3,108	686,023	(2,777)	(115)	(26)	(325)

[a]. For comparison to emission reduction goals of AB 32, greenhouse gas emissions must be reduced by an average of 174 million metric tons of CO_2 equivalents annually.

Table III-27: Annual Criteria Pollutant Emissions Avoided (MT) in Alternative Management Scenario (Post-5-Year Phase-in)

Source	NO_x	PM10	PM2.5	SO_x
Cylinder Manufacturing (emissions will occur at seven point sources)	1.8	1.7	0.4	-2.7
Cylinder Recycling Credits	0.1	0.1	0.0	5.3
Transport (emissions will occur between CA and seven manufacturing states: IL, ID, KY, OH, MD, RI, WI)	-68.8	-1.9	-0.3	-1.8
Total	-66.9	-0.1	0.1	0.8

Figure III-5 graphically compares the cumulative GHG emissions in BAU and the alternative management scenario from 2010 to 2050. Figure III-6 compares the annual GHG emissions over the same time frame.

Figure III-5: Cumulative Net GHG Emissions (2010-2050)

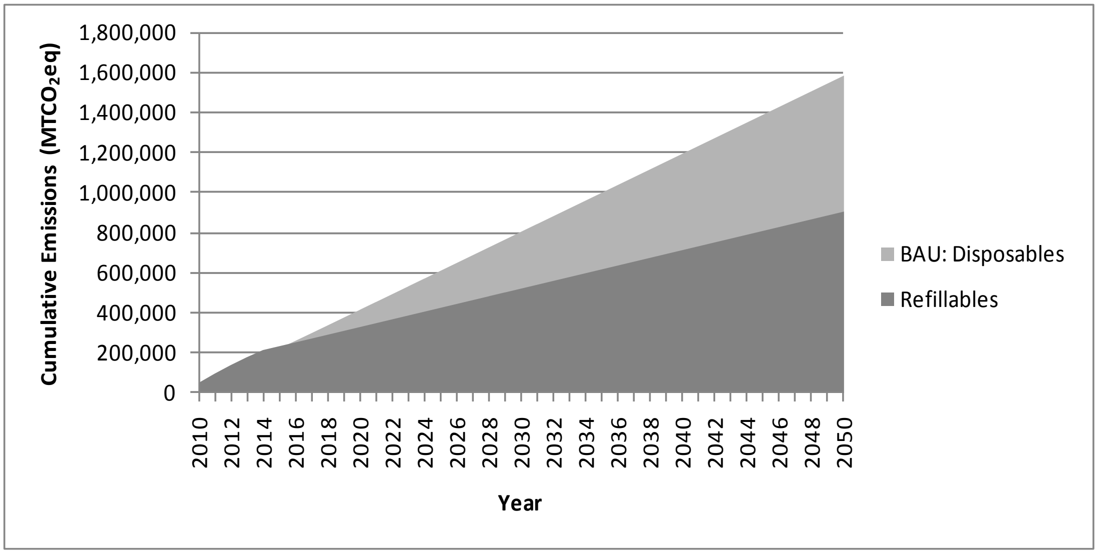


Figure III-6: Annual Net GHG Emissions (2010-2050)

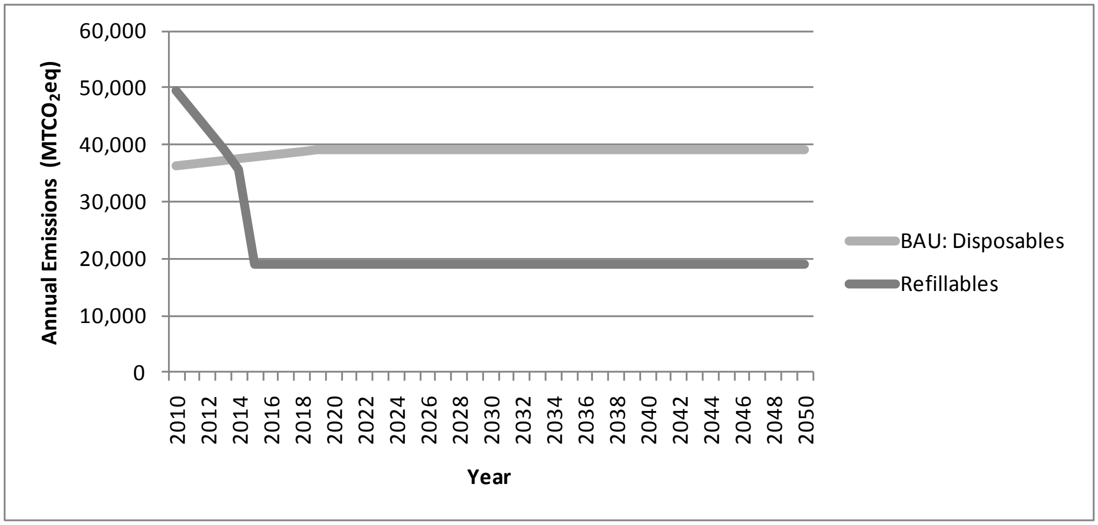


Table III - 28 presents the net criteria pollutant emissions resulting from point and non-point sources in the refillables scenario. Incremental pollutant emissions from non-point (transport) will be emitted between California and the seven manufacturing states (of Illinois, Indiana, Kentucky, Maryland, Ohio, Rhode Island and Wisconsin). The incremental criteria pollutant emissions from point sources under this scenario in the near-term are not significant;[79] no more than 71 MT of criteria pollutants are projected to be emitted across seven manufacturing facilities per year; on a per facility-basis, the maximum cumulative increase in annual emissions will be approximately 10 MT.

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[79] A “major stationary source,” as defined in Section 112 of the Federal Clean Air Act, is one with the potential to emit 10 tons per year, or more, of any hazardous air pollutant listed pursuant to Section 112(b) of the Federal Clean Air Act; or 25 tons per year, or more, of any combination of hazardous air pollutants listed pursuant to Section 112(b) of the Federal Clean Air Act. According to ARB’s “Authority to Construct” definitions, a major stationary source may also be one with a potential to emit more than: 25 tons per year of nitrogen oxides, 25 tons per year of volatile organic compounds, 100 tons per year of sulfur dioxide, 100 tons per year of carbon monoxide, 100 tons per year of PM10, or 100 tons per year of a regulated air pollutant.

Table III - 28: Annual Incremental Criteria Pollutant Emissions in Refillables Scenario (MT)

Year	NOx			PM10			PM2.5			SOx		
	Point	Non Point	Total	Point	Non Point	Total	Point	Non Point	Total	Point[a]	Non Point	Total
2010	27.1	20.1	47.2	21.4	0.6	21.9	6.1	0.1	6.2	70.8	0.5	71.3
2015	-1.9	68.8	66.9	-1.7	1.9	0.1	-0.5	0.3	-0.1	-2.6	1.8	-0.8
2020	-1.9	68.8	66.9	-1.7	1.9	0.1	-0.5	0.3	-0.1	-2.6	1.8	-0.8
2025	-1.9	68.8	66.9	-1.7	1.9	0.1	-0.5	0.3	-0.1	-2.6	1.8	-0.8
2030	-1.9	68.8	66.9	-1.7	1.9	0.1	-0.5	0.3	-0.1	-2.6	1.8	-0.8
2035	-1.9	68.8	66.9	-1.7	1.9	0.1	-0.5	0.3	-0.1	-2.6	1.8	-0.8
2040	-1.9	68.8	66.9	-1.7	1.9	0.1	-0.5	0.3	-0.1	-2.6	1.8	-0.8
2045	-1.9	68.8	66.9	-1.7	1.9	0.1	-0.5	0.3	-0.1	-2.6	1.8	-0.8
2050	-1.9	68.8	66.9	-1.7	1.9	0.1	-0.5	0.3	-0.1	-2.6	1.8	-0.8
2010–2020	120.3	651.1	771.4	93.0	17.9	110.9	26.8	3.3	30.1	333.1	16.6	349.7
2010–2050	63	2,714	2,777	41	75	115	12	14	26	256	69	325

[a] Due to the large SO_x emission factor for copper, refillable cylinder manufacture results in higher emissions of SO_x per cylinder than does disposable cylinder manufacture.

III.7.3. Cost Effectiveness

By banning disposable cylinders, an estimated 0.7 $MMTCO_2eq$ can be avoided by 2050, though at significant cost. The incremental costs per GHG emission reduction of the alternative management scenario are presented in Table III-29. Cost effectiveness is greatest following the five-year phase-in period, once the refillable cylinder fleet reaches maturity. The primary cost driver is transport; if cylinder evacuation/refilling stations were to be established within California, the cost effectiveness would be greater.

Table III-29: Total Incremental Costs and GHG Emissions Avoided (2010-2050)

Total Costs and GHG Emissions Avoided	HFCs	Total
Incremental Cost (NPV $ millions)	$176	$266
GHG Emissions Avoided ($MMTCO_2eq$)	0.69	0.69
NPV Cost Effectiveness ($/$MTCO_2eq$)	$254	$388

In reality, compliance with ARB's Refrigerant Management Program is highly uncertain and difficult to enforce. Under a scenario of non-compliance with this program, net GHG emissions avoided by transitioning to refillable cylinders would be approximately 14 $MMTCO_2eq$, and cost effectiveness would be $14/$MTCO_2eq$ for HFCs only, and $20/$MTCO_2eq$ for both HFCs and ODS.

III.7.4. Recommendations

By replacing disposable cylinders with reusable cylinders over a five-year phase-in period, an estimated 0.7 $MMTCO_2eq$ can be avoided by 2050, though at significant cost ($254/$MTCO_2eq$ for HFCs by 2050). However, actual emission reductions and cost-effectiveness of this measure may be substantially higher if compliance with ARB's Refrigerant Management Program is low—i.e., up to 14 $MMTCO_2eq$ avoided at $14/$MTCO_2eq$ for HFCs by 2050. These results underscore the need for ARB to monitor and enforce the Refrigerant Management Program provision for cylinder evacuation at EOL and consider alternative policies to further reduce emissions if needed. To this end, additional research could be conducted to assess measures to promote compliance with federal and CA refrigerant recovery regulations at EOL.

III.7.5. Additional Considerations

Due to time constraints, a number of simplifications were made in this analysis. A more complete LCA would require additional considerations and a more nuanced methodology. These considerations include:

- A range of BAU heel emissions based on: compliance with new evacuation requirements; technician techniques/skill levels (e.g., consideration of the cylinders currently handled by trained/certified technicians vs. do-it-yourselfers); and implementation of best practices (see Appendix C: Best Management Practices).
- Emission impact associated with cylinders of varying sizes (e.g., from 20 to 50 lbs.) and containing different refrigerant types.
- Emissions and costs impacts associated with variations in the percent of cylinders reaching different fates (e.g., percent of disposable cylinders that are recycled vs. landfilled at EOL; percent of refillable cylinders that are refurbished/ re-circulated vs. reach ultimate disposal).
- Projected market changes that will affect the number of 30-lb cylinder sales through 2050, as well as the types of refrigerant sold in those cylinders.

- Alternative industry responses to cylinder management scenarios (e.g., establishing new cylinder evacuation/refilling facilities within California, which would eliminate the need to transport used cylinders across the country).

In addition, several other considerations should be borne in mind when weighing the cylinder management options. In particular, cylinder quality issues should be considered in addition to the safety concerns noted earlier. Regarding cylinder quality, disposable cylinders may be prone to valve leakage whereas the refillables have better quality valves. According to one industry representative in Australia, disposable cylinders have a “burst disc,” such that if the cylinder is subjected to over-pressure, the contents will escape to the atmosphere (A-Gas Australia 2009). Conversely, refillable cylinders are fitted with a safety relief valve which resets after the over-pressure has been released.

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III.9. Appendix A: Review of Cylinder Evacuation Times, Vacuum Pressures, and Refrigerant Heels

Based on repeated tests performed by a skilled refrigerant technician, Figure III-7 presents the quantity of refrigerant removed when a cylinder is evacuated from 0 psig down to a 25-inch vacuum. As shown, the rate of refrigerant removal decreases as the vacuum increases. Beyond 15-inches, a deeper vacuum results in negligible refrigerant removal. (Berkan 2009)

Figure III-7: Refrigerant Removal at Increasing Levels of Vacuum

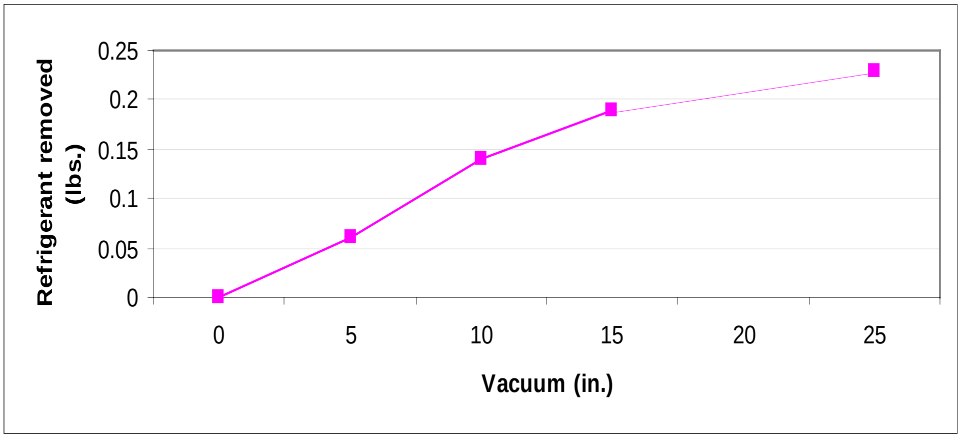
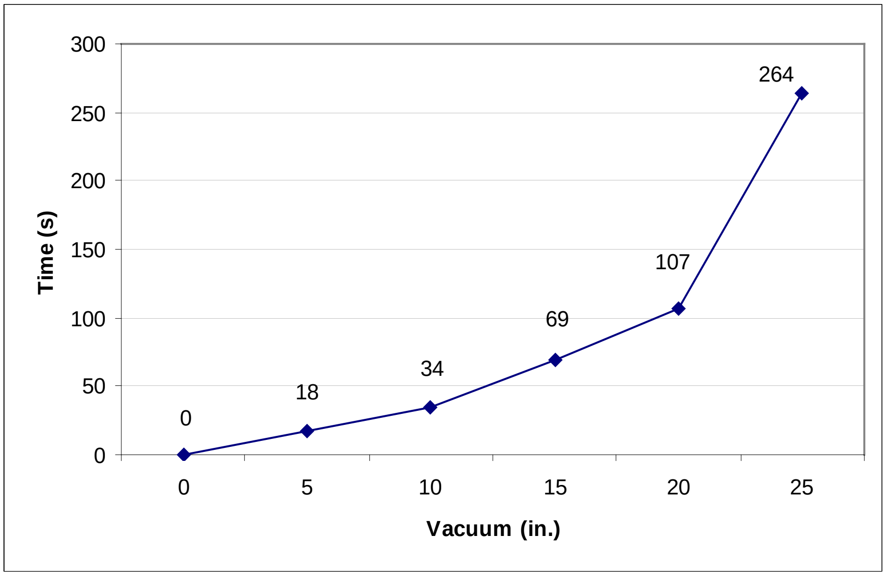


Figure III-8 presents the time needed to evacuate the cylinder down to each level of vacuum. This test was completed using high-volume recovery equipment that evacuated cylinders to a 15-inch vacuum in just over 1 minute. However, it is believed that even a smaller, hand-held recovery device could evacuate the cylinder to 15-inches within just three minutes. (Berkan 2009)

Figure III-8: Time Required to Evacuate Cylinders to Specific Vacuum Levels



The quantity of refrigerant remaining in “empty” cylinders is highly uncertain. Estimates range from 1.85% to 6%. Table III-30 presents the data sources used to calculate average heel remaining when cylinders are deemed empty by technicians. Based on previous research and communication with industry before the California heel evacuation requirements existed (per ARB’s Refrigerant Management Rule), it was assumed that about 70% of non-refillable cylinders reaching EOL were recycled or disposed by technicians without evacuation; the remaining 30% were assumed to be evacuated down to the ARI standard of 15-inch mercury vacuum. This ratio of non-evacuated to evacuated cylinders was applied to the data sources that reflected the average heel across all cylinders to determine the average estimated heel in cylinders deemed empty without any evacuation attempts. These estimates were then averaged to get a 3.7% heel remaining in a spent cylinder.

Table III-30: Data Sources for Heel Estimates

Data Source	Refrigerant Heel Remaining In Spent Cylinder	Lbs Heel (30 lb Cylinder)	Explanation of Estimate
Airgas (2007)	3.00%	0.90	Average representing all cylinders, deemed empty and/or evacuated
American Refrigeration Supplies (2010)	3.70%	1.11	Represents non-evacuated cylinders
Berkan (2008)	6.00%	1.80	Quantity remaining once cylinder is deemed empty
National Refrigerants, Inc. (2010)	1.95%	0.59	Quantity remaining once cylinder is deemed empty
Perrin-Quarles (2007)	1.85%	0.56	Based on small sample size; unclear if estimate is for cylinders evacuated by technicians prior to disposal or not; does not include consideration of abandoned cylinders
Weighted Average	3.7%	1.11	

III.10. Appendix B: Deposit/Refund Scheme and Rental Fee for Cylinders

To promote the return of disposable cylinders for heel evacuation, a deposit/refund scheme could be implemented. Under such a scheme, a technician would pay a deposit per cylinder at the time of purchase, and receive a full refund once the cylinder is returned. The same deposit/refund scheme could be used to promote the return of refillable cylinders for evacuation and refilling. In addition, a monthly rental fee could be applied to refillable cylinders, to encourage their timely return.

While an in-depth cost assessment of such a deposit/refund scheme or rental fee is beyond the scope of this analysis, indicative costs can be estimated. Assuming a labor rate of $40 for program implementation and administration, a one minute labor time for each cylinder, and a 97% return rate of cylinders, a deposit/rebate program would cost approximately $118,400 annually for administration. However, this cost could be offset by revenue from unclaimed rebates (i.e., for lost or otherwise unreturned cylinders). For instance, if a deposit of $10 was placed on each disposable cylinder, a 3% non-return rate would garner approximately $219,700 each year in revenue.

Similarly, a rental fee placed on refillable cylinders could generate revenue from slow cylinder return. In the UK, a rental fee of about £3/month is placed on each cylinder in addition to the £20-30 deposit (A-Gas UK 2009). Consequently, refillable cylinders are returned promptly, with each one being refilled up to three or four times per year. Assuming a lower rental fee of $1/month, and a slightly longer return time of 9 months, $6.4 million in revenue could be generated annually.

III.11. Appendix C: Best Management Practices

In addition to the BAU assumptions and assessment, there exists a parallel set of management practices known collectively as best management practices. For the purpose of this lifecycle analysis, these best practices may be described as currently feasible, available, and often cost-efficient refrigerant management practices that result in less environmental impact, but may not yet be widely practiced. Although a detailed analysis is beyond the scope of this particular research, a summary of best practices is provided below. Additionally, a cylinder recycling pilot program that incorporates current refrigerant heel best management practices is also described below.

Cylinder Recycling Pilot Study

Non-refillable refrigerant cylinders, when properly evacuated and recycled, create less environmental impact than non-refillable refrigerant cylinders that are landfilled without prior evacuation (ARS 2010). American Refrigeration Supplies, Inc. (ARS) launched a refrigerant cylinder recycling program in the Phoenix, Arizona area in November 2009. Preliminary results indicate that a voluntary, industry-led recycling program may result in significant emission reductions from disposed refrigerant cylinders.

ARS provided free recycling of disposable cylinders at nine locations for contractors and technicians. A disposable cylinder recycle awareness campaign was launched simultaneously, with the objective to educate contractors and technicians on proper recycling of disposable cylinders, with three main messages:

1. Don’t vent;
2. Close valve; and
3. Recycle disposable cylinders at participating distributor locations.

Initial recycling results based on the return of 306 disposed HCFC-22 cylinders showed that cylinders came back in three main states of valve condition and refrigerant capacity:

1. Open valve, empty cylinder – 26% of cylinders (assume significant emissions from these cylinders);
2. Closed valve, empty cylinder – 13% of cylinders (cylinders could have been evacuated prior to recycling, although the worst-case scenario is that they were vented completely prior to closing the valve – potentially significant emissions);
3. Closed valve, refrigerant remaining in cylinder – 61% of cylinders containing on average, 1.12 pounds per cylinder (ideal recycling scenario, refrigerant can be recovered and reused).

The recycling program findings indicate that significant emission reductions can be made by educating contractors and technicians to return used cylinders with the valve closed. Between November 2009 and February 2010, the number of open valve returns decreased from 26% to 23%, a 12% annual rate of decline, attributed to the awareness campaign.

The other findings from the pilot program indicate that contractors and technicians are more likely to recycle used cylinders if the program is free to them, and convenient, i.e., used cylinders can be recycled at the same locations where new cylinders are purchased. The entire cost of the recycling program thus far has been approximately neutral, with the value of recovered refrigerant the key to sustaining the program.

III.12. Appendix D: Stakeholder Comments to Draft Version of LCA

Nine stakeholders submitted 105 separate comments on earlier draft versions of the LCA on refrigerant cylinder management.

The following list summarizes the comments, with similar comments grouped together. It should be noted that because the initial LCA was written before the California Refrigerant Management Plan rule had taken effect in January 2011; the initial LCA did not include mandatory cylinder evacuation requirements as part of business-as-usual. The updated LCA corrects this assumption.

Many comments from stakeholders submitted in 2009 and 2010 have been rendered moot as a result of the new business-as-usual assumption changing from a used refrigerant cylinder containing a significant heel (remaining refrigerant) of 1.8 lbs, to a new BAU that assumes only 0.05 lbs of refrigerant. These older comments from 2009 and 2010 are not addressed in this section, as they no longer correlate to the revised 2011 version of the LCA. The remaining comments have been addressed in the revised LCA, with the resulting response/action summarized after each comment category. The remaining comments have been directly incorporated into the LCA input assumptions, and the results were refined as a result of the stakeholder comments. A few comments addressed issues that were not within the scope of work for this particular LCA project. For these comments, they were addressed in a qualitative manner (non-quantitative), with an accompanying discussion that did not change emissions or cost results. These comments are noted in the summary titled “Comments Resulting in Qualitative Discussion.”

III.12.1. Comments Summary:

1. Comment: The LCA cites input from few industry representatives, which does not reflect the diversity of those in the refrigerant industry that practice cylinder handling.

Response/Action: Researchers solicited input and feedback from 37 separate industry stakeholders, resulting in comment feedback from nine stakeholders, greatly improving the LCA’s accurate representation of BAU practices and cost, and also the estimated cost-benefit of alternative cylinder management scenarios.

2. Comment: The LCA significantly underestimates the cost of managing refillable cylinders.

Response/Action: Additional research on the management of refillable cylinders resulted in improved cost input assumptions, which are reflected in the updated LCA.

3. Comment: The report assumes that once deemed empty, cylinders are abandoned and dumped. This assumption does not appear to be based on actual data.

Response/Action: No official data is collected on refrigerant cylinder recycling in California, and industry estimates range from low recycling rates of 15 percent, to near-perfect recycling rates of 100 percent. Based upon additional research and input from numerous industry stakeholders, the recycling rate was increased to 75 percent of empty cylinders are assumed to be properly recycled.

III.12.2. Comments Resulting in Qualitative Discussion:

1. Comment: The refillable cylinder scenario does not account for the increased cost associated with storage and handling. For example, additional warehouse space may have to be rented to store refillable cylinders, resulting in significant cost increase above BAU.

Response/Action: As described in section III.4.5. “Storage and Handling” of this revised LCA, the amount of additional storage space required is highly uncertain, depending upon individual facility storage capacities, which could result in no added cost to a distributor or user of cylinders, to a significant added cost per business. Unfortunately, the level of detail required for this cost analysis was not within the scope of work of this LCA research, and is not included.

2. Comment: The impact of the additional weight of refillable cylinders (compared to BAU non-refillable cylinders) is not accounted for in terms of cost of health and safety issues. Workers carrying the heavier refillable cylinders are more likely to suffer back injuries on the job, resulting in disability, pain and suffering, lost work, and an overall cost to the business.

Response/Action: The new added section III.4.6. “Health and Safety” of this revised LCA addresses the refillable cylinder impacts on worker health and safety in a qualitative manner, although it is beyond the scope of work of this particular LCA to conduct a cost-benefit analysis of the worker health and safety issues of using refillable cylinders versus non-refillables. The added cost of business may range from negligible to very significant, depending upon each individual business’ approach to worker health and safety.

III.13. Appendix E: Report Figures presented as Data

The following tables show the data which ICF used to develop the figures and graphs presented in Part III. LCA on Disposable Refrigerant Cylinders. In each case, numbered tables are followed by a figure reference in brackets (e.g., from Figure III-xx), and the title of the relevant figure as it is shown in the body of the report.

Table III-31 (from Figure III-4): Annual GHG Emissions in BAU (2019-2050)

Emissions Source	Total GHG Emissions (MTCO2eq)
Heel emissions	27,532
Transport emissions	5,043
Manufacturing and recycling emissions	6,454

Table III-32 (from Figure III-5): Cumulative Net GHG Emissions (2010-2050)

Year	BAU: Disposables	Refillables
2010	36,220	49,439
2011	72,753	95,556
2012	109,598	138,249
2013	146,754	177,419
2014	184,223	212,966
2015	222,004	231,822
2016	260,097	250,740
2017	298,502	269,720
2018	337,219	288,763
2019	376,249	307,869
2020	415,278	326,974
2021	454,307	346,079
2022	493,336	365,184
2023	532,365	384,290
2024	571,395	403,395
2025	610,424	422,500
2026	649,453	441,605
2027	688,482	460,711
2028	727,512	479,816
2029	766,541	498,921
2030	805,570	518,026
2031	844,599	537,132
2032	883,628	556,237
2033	922,658	575,342
2034	961,687	594,448
2035	1,000,716	613,553
2036	1,039,745	632,658
2037	1,078,775	651,763

Year	BAU: Disposables	Refillables
2038	1,117,804	670,869
2039	1,156,833	689,974
2040	1,195,862	709,079
2041	1,234,891	728,184
2042	1,273,921	747,290
2043	1,312,950	766,395
2044	1,351,979	785,500
2045	1,391,008	804,605
2046	1,430,038	823,711
2047	1,469,067	842,816
2048	1,508,096	861,921
2049	1,547,125	881,027
2050	1,586,154	900,132

Table III-33 (from Figure III-6): Annual Net GHG Emissions (2010-2050)

Year	BAU: Disposables	Refillables
2010	36,220	49,439
2011	36,533	46,116
2012	36,845	42,693
2013	37,157	39,170
2014	37,469	35,547
2015	37,781	18,856
2016	38,093	18,918
2017	38,405	18,980
2018	38,717	19,043
2019	39,029	19,105
2020	39,029	19,105
2021	39,029	19,105
2022	39,029	19,105
2023	39,029	19,105
2024	39,029	19,105
2025	39,029	19,105
2026	39,029	19,105
2027	39,029	19,105
2028	39,029	19,105
2029	39,029	19,105
2030	39,029	19,105
2031	39,029	19,105
2032	39,029	19,105
2033	39,029	19,105
2034	39,029	19,105
2035	39,029	19,105
2036	39,029	19,105

Year	BAU: Disposables	Refillables
2037	39,029	19,105
2038	39,029	19,105
2039	39,029	19,105
2040	39,029	19,105
2041	39,029	19,105
2042	39,029	19,105
2043	39,029	19,105
2044	39,029	19,105
2045	39,029	19,105
2046	39,029	19,105
2047	39,029	19,105
2048	39,029	19,105
2049	39,029	19,105
2050	39,029	19,105

Table III-34 (from Figure III-7): Refrigerant Removal at Increasing Levels of Vacuum

Vacuum	Quantity of Refrigerant Removed (lbs)
0	0
5	0.06
10	0.14
15	0.19
20	—
25	0.23

Table III-35 (from Figure III-8): Time Required to Evacuate Cylinders to Specific Vacuum Levels

Vacuum	Time
0	0
5	18
10	34
15	69
20	107
25	264

IV. LCA on Construction and Demolition (C&D) Foam

IV.1. Introduction

The foam building/construction sector is a potentially significant source of ozone depleting substances (ODS) and greenhouse gases (GHGs). In fact, estimates of banked and emitted ODS and hydrofluorocarbons (HFCs) indicated that foam applications accounted for 61% of the total ODS and HFC banks in the US in 2005 (Caleb 2010). Significant emission reductions may be possible through proper handling techniques during foam production, installation, and use, and during end-of-life management of construction foams used for insulating purposes.

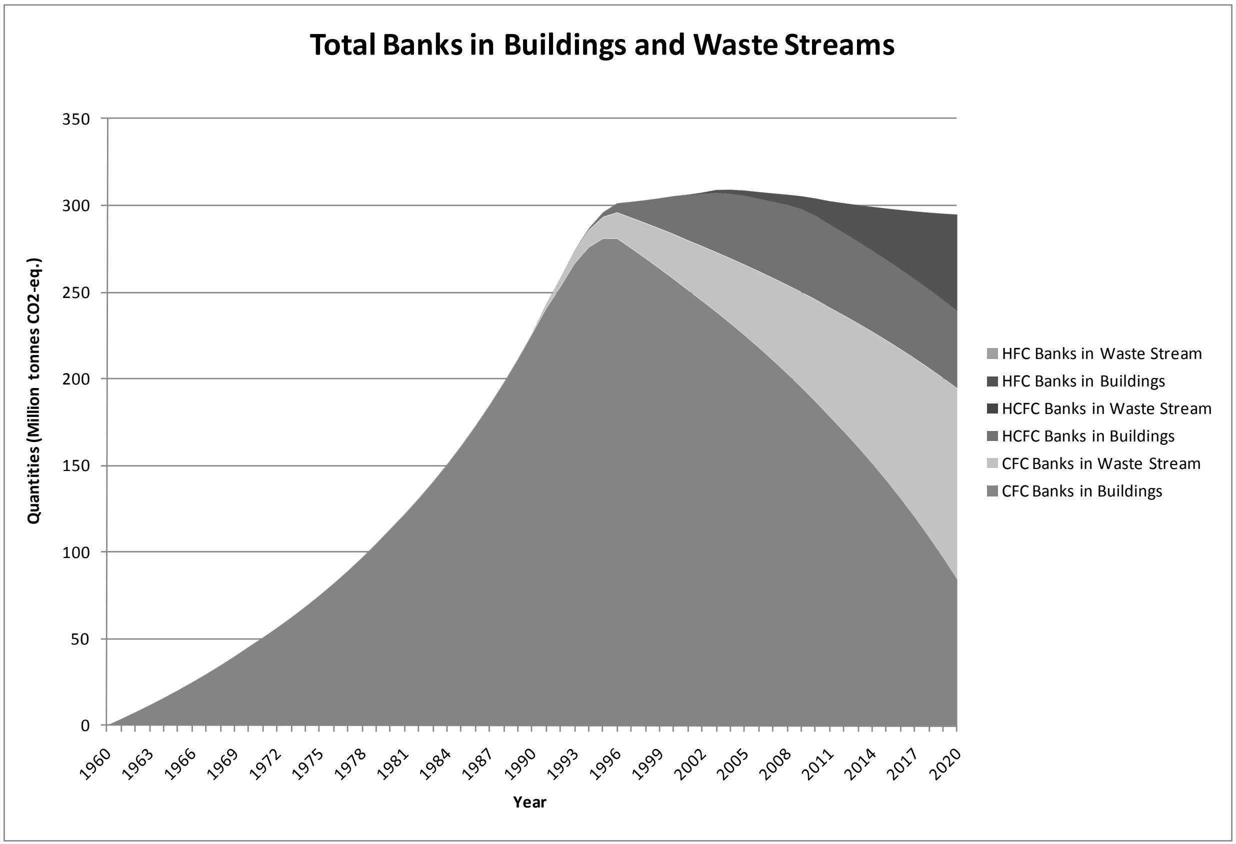
A report was recently prepared for the ARB by Caleb Management Services Ltd. (2010), on *Developing a California Inventory for ODS and HFC Foam Banks and Emissions from Foam.* This report characterized foam blowing agent banks according to product and application; characterized current foam production, use, and end-of-life fates by product/application; characterized historical ODS blowing agents in use, their replacements, and not-in-kind technology trends; and developed an emissions model to estimate blowing agent emissions through 2020 under business as usual and other scenarios. Foam sectors analyzed included building/construction, appliance, transport refrigeration, and marine buoyancy foams. Based on the assessment, total ODS/HFC foams banks peaked in 1996 at nearly 364 million metric tons carbon dioxide equivalent (MTCO$_2$eq).

To date, banks have reduced by around 40 million MTCO$_2$eq and are expected to reduce by a further 60 million MTCO$_2$eq by 2020. Buildings constitute the biggest single location for ODS banks, with banks of all other sources combined never exceeding 25% of the total—although these sources may be more emissive. Caleb estimates current emissions from the various sources at 4.4 million MTCO$_2$eq, split between 0.6 million MTCO$_2$eq from HFCs, and 3.8 million MTCO$_2$eq from ODS.

Blowing agent emission trends from the building sector reveal that, after 2007, the decommissioning stage represents the largest single source of emissions; by 2020, emissions are expected to exceed 4 million MTCO$_2$eq annually, all of which are associated with ODS. Although foam emissions from the building decommissioning stage (end-of-life) are significant, they only represent about half of all ODS/HFC emissions from building insulating foam in California, with the remainder of emissions occurring at the time of foam manufacture (~13% loss) and during the useful lifetime of the foam (~38% loss). Therefore, even the most comprehensive program to manage end-of-life foam from buildings could only result in reducing up to 50% of foam emissions from the building sector.

Figure IV-1 presents the total banks of CFC, HCFC, and HFC blowing agents contained in building foams. (Caleb 2010)

Figure IV-1: Total Banks in Building and Waste Streams



Caleb (2010) also analyzed various options for reducing emissions of ODS/HFCs from these sectors, noting the technical potential to avoid 27-37% of baseline annual emissions of high-GWP gas emissions from the foam sector in 2020, equivalent to up to 3 million $MTCO_2$eq. However, the report noted that while the management of building foams at end-of-life provides a significant opportunity for mitigation even as early as 2020, the cost may be prohibitive when compared with other options available to the state's Climate Action Plan. Based on Caleb (2010), it is assumed that the recovery and destruction of construction and demolition foam is only feasible for polyurethane (PU) panels. For all other foam types, the costs of recovery would be prohibitive (approximately \$300/$MTCO_2$e reduction), considering the technical difficulty of foam separation and processing (BRE 2010, as reported in Caleb 2010). For example, spray-on insulating foam clings to surfaces forming a tight seal, and to recover this foam at the time of building decommissioning, the spray-on foam would have to be manually scraped or chiseled off of the sheet rock or building material to which it is bonded, which would be extremely labor-intensive and costly. Even the commonly used insulating boardstock is time-consuming to separate from the co-mingled C&D waste typically found at building decommissioning (TEAP 2009).

The only building insulation foam that is currently separated from C&D debris in California is steel-faced PU panels because the steel facing has economic value and is cost-effective to recover. Indeed, according to Caleb (2010), an estimated 80% of the PU panels in California are separated from the C&D waste and sent to a metal shredder, where the panel is shredded, with the metal recovered and the foam landfilled as shredder fluff. The remaining 20% of PU panels are assumed to go directly to landfills. Therefore, this analysis quantitatively explores only the recovery and destruction of foam from PU panels.

PU panels comprise an estimated 10% of all high-GWP-containing foam insulation currently used in buildings, with the remaining 90% comprised of boardstock (84%), and spray-on foam (6%) (FTOC 2006, 2010). Based on the best available data, it is reasonable to conclude that at this time, it is not economically feasible to recover and manage the 90% of high-GWP foam building insulation represented by board stock and spray foam.

This analysis is based on the baseline stock and emission estimates developed by Caleb for the building foams sector.

IV.2. Background

Insulation foams in California are used in a variety of building products, including panels in cold storage facilities or refrigerated warehouses, primary insulation materials contained within brickwork or steel, and spray-applied in retrofit internal and external insulation. Foam types include polyisocyanurate (PIR) board stock and extruded polystyrene (XPS) board stock, polyurethane (PU) panels, and PU spray foam. Caleb (2010) indicates that PIR foam accounts for more than 50% of the foam consumption in California from 1960 to 2009. The characteristics and primary uses of each construction foam type are summarized below:

- *Board stock:* used often in roof and wall insulation in multi-layer residential and commercial building walls and roofs.
- *Sandwich panels:* used for insulating cold storage facilities, cold rooms, and in doors. Panels contain foam between two facing materials, typically steel, aluminum or glass fiber reinforced plastic sheets. These are typically 80% metal by weight.
- *Spray foams:* manufactured at the point of use and are sprayed into place to provide insulation on a range of irregular surfaces; often used to retrofit existing roofs to improve insulation performance in pipe and tank insulation.

The recovery of construction foam during building retrofits or demolition is more difficult than foam removal from appliances, given the challenges associated with physically separating foam insulation from the rest of the demolished material. The ability to extract foam-containing elements from demolition waste depends largely on the original form of the foam and how it was applied. For example, PU spray foams are usually applied directly onto building walls and have natural adhesive properties. As such, the process of removal would be complex and time-intensive. Furthermore, it is possible that a portion of the ODS blowing agent contained in the foam insulation would be released during separation. These issues of complexity, time, and blowing agent loss were studied by the Japanese Technical Committee on Construction Materials (JTCCM) in 2005, which concluded that it was “not practical to mandate recovery based on observations concerning practicality and cost” (TEAP 2009). However, other types of construction foams may present greater opportunities for separation and recovery, such as steel-faced sandwich panels or PU board stock, depending on the application and location of the material. In fact, since buildings/warehouses are relatively easily dismantled, PU panel foam can be technically recovered either for re-use to clad another space or for channeling to the destruction stream.

There is currently no national or California legislation regulating the handling of waste ODS/F-gas foams from building construction and demolition activities. However, potential GHG savings may be associated with the proper recovery and destruction of high-GWP construction foams. Indeed, while the recovery and collection of foams from buildings may require significant effort and cost at time of building demolition or reconstruction, Caleb (2010) estimates that foam recovery and destruction from such applications may represent a means of reducing cumulative emissions savings of up to 8.7 million $MTCO_2eq$ for all GHGs, and up to 1.3 million $MTCO_2eq$ for HFCs alone by 2020.

IV.3. Purpose

The analysis presented here explores the life cycle incremental costs and environmental benefits associated with the recovery, separation, and destruction of PU panel foams in the building/construction sector at time of building demolition.[80] Due to the technical difficulty of segregating and destroying other types of foam at time of building demolition, this analysis only looks at steel-faced PU panels.

The remainder of the report is organized as follows:

- Section IV.4 describes current business as usual foam management practices based on the inventory developed by Caleb (2010);
- Section IV.5 describes the alternative management scenario to be assessed in the analysis;
- Section IV.6 presents the key assumptions used to estimate emission and costs, as well as additional assumptions developed to estimate incremental costs and incremental emissions in the alternative management scenario;
- Section IV.7 presents the results, including an assessment of costs, environmental benefits and cost-effectiveness;
- Section IV.8 presents recommendations;
- Section IV.9 presents additional considerations; and
- Section IV.10 provides a list of references used for this analysis.

IV.4. Defining Business as Usual (BAU)

Construction and demolition waste accounts for approximately 16% of California's annual 40 million ton waste stream. A small percent of the foam may be classified as municipal solid waste (MSW) and sent to a WTE facility. However, most construction and demolition (C&D) waste is typically separated at waste transfer stations and therefore would not become part of the MSW waste stream. Most commonly, C&D building foam is combined with other C&D mixed waste loads that are considered non-hazardous and landfilled. In developing banks estimates, Caleb (2010) assumes that 20% of PU panel foams are directly landfilled, while 80% are open shredded (to recover and recycle the metals) and then landfilled. Buildings (and hence, building foam) are estimated to have a lifetime of 30 years; therefore, new buildings built in 1980 are assumed to be demolished or refurbished in 2011. Because PU panels only began being used in 1985 (in cold storage facilities, followed by commercial buildings in 1995, and multi-family houses in 2005)[81], the first year of PU panel disposal is assumed to be 2016.

Caleb (2010) assessed building foam banks based on buildings stock data for residential, non-residential, and commercial buildings from a variety of sources including the California State-wide Residential Appliance Saturation Study (RASS), the US Census Bureau, and the California Energy Commission. Based on this data and assumptions about the volume of foam per

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[80] Buoyancy applications (e.g., boats, surf boards, etc.), reefers, and other transport applications are not quantitatively addressed in this analysis, as they contribute significantly less to the total ODS and HFC banks than the construction foams sector.

[81] PU panels are not used in single-family houses in California.

building and average density of 40 kg/m^3, Table IV-1 presents the estimated quantity of PU panel foam reaching EOL each year from 2010-2050.

Table IV-1: Quantity of PU Panel Foam in CA Buildings Reaching EOL, 2010–2050 (Caleb 2010)

Year	Building Demolition PU Panel Foam (MT)		
	Multi-Family	Commercial	Cold Storage
2010	—	—	—
2015	—	—	—
2020	—	—	20
2025	—	—	55
2030	—	1,158	79
2035	—	1,619	111
2040	2,108	4,675	161
2045	5,787	6,750	232
2050	7,947	9,747	336
Total	70,065	103,945	4,240

Note: Totals shown do not match the sum of individual entries as shown in this table because totals are for all years 2010-2050, while entries reflect yearly values shown in 5-year increments.

Blowing agent represents approximately 8% by weight of PU panel foam. Given this blowing agent/foam ratio and accounting for in-use blowing agent losses of 0.25% per year over the 30-year building lifetime, Table IV-2 presents the total quantity of blowing agent available at PU panel EOL from 2010-2050.[82]

Table IV-2: Quantity of blowing agent (MT) in PU panel foam in CA Buildings Reaching EOL, 2010-2050

Year	CFC 11	HCFC 141b	HFC 245fa	HCs
2010	—	—	—	—
2015	—	—	—	—
2020	1.5	—	—	—
2025	2.0	2.0	—	—
2030	—	91.5	—	—
2035	—	19.2	57.6	51.2
2040	—	—	256.9	256.9
2045	—	—	472.5	472.5
2050	—	—	667.1	667.1
Total (MT)	32.6	688.7	6,256.8	6,212.4
Total (MMTCO$_2$Eeq)	0.12	0.48	5.94	0.07

Note: Totals shown do not match the sum of individual entries as shown in this table because totals are for all years 2010-2050, while entries reflect yearly values shown in 5-year increments.

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[82] Caleb (2010) developed assumptions of blowing agent use and transitions in California: CFC-11 accounted for 100% of the BA market until 1993, when HCFC-141b began penetrating the market. This HCFC completely replaced CFC-11 by 1996 and controlled the market until HFC-245fa began penetrating in 2000. Pentane entered the market in 2001, and as of 2005 HFC-245fa and pentane both represent 50% of the new PU foam panel market.

> Hydrocarbons (HCs) are estimated to have a GWP of less than 25, according to TEAP (2009). However, for the purposes of this assessment, non-ODS, non-HFC blowing agents are assumed to have a GWP of zero, as they are a functionally negligible GHG source compared to high-GWP foam expansion agents.

As previously mentioned, it is assumed that 20% of PU panel foam in the baseline is landfilled directly, while the remaining 80% is open shredded (to recover and recycle the metals) and then landfilled.[83] These assumptions are based on likely activities rather than actual experience, since there has been minimal EOL experience to date given the relatively recent use of foam panels in buildings. Emissions assumptions associated with these foam handling processes are detailed in Section IV.6 below.

Due to available landfill space, the complexity associated with separating foams from other C&D waste fractions, the current disinclination to segregate demolition waste, and the relatively low cost of landfilling, it is likely that demolition foam will continue to be landfilled unless specific mandates require alternative practices. Because C&D foam waste is crushed before being landfilled, significant emissions occur at time of disposal using current/projected practices.

IV.5. Management Scenarios

This analysis considers the emissions reductions and incremental costs associated with separating and recovering blowing agent from PU panel foam at two levels of program participation: 25% of C&D panels reaching EOL and 50%.

Specifically, the alternative management scenario explored in this analysis assumes that:

- PU panel foam separated from other C&D waste and trucked to an appliance recycling facility.
- At the appliance recycling facility, foam panels are processed in a fully-automated/enclosed appliance shredder which separates the blowing agent from the foam fluff.
- Foam blowing agent is sent for destruction using an approved technology,[84] while the foam fluff is sent to a landfill.

Currently, this type of C&D foam processing (i.e., destruction with prior blowing agent blowing agent recovery in a fully-automated/enclosed appliance shredder) is conducted in a variety of European countries, but not in the United States. Specifically, in Europe steel-faced panels are cut down to 2 meters long before processing at appliance recycling facilities. The ODS gases are captured, shredded metals are collected for recycling, and foam fluff is bagged for further use or landfill. In California, there are three dedicated appliance recycling facilities that recover foam from appliances that could potentially also be used for processing PU panels from C&D waste. One of these facilities, located in Hayward, CA, already has a technology that could handle composite panel and non-panel foam waste from C&D sites via a degassing system.

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[83] Caleb (2010) estimates emissions associated with these processes at 20% for landfilling and 25% for open shredding followed by landfilling. Annual losses after landfilling or shredding/landfilling are 0.5% and 2%, respectively. In this analysis, emissions assumptions are based on additional research and consultation with industry experts, and are consistent with the assumptions used in the appliance EOL LCA.

[84] Approved technologies for destroying ODS are presented in Annex II of the Report of the 15th Meeting of the Parties of the Montreal Protocol. For (dilute) ODS foam, these technologies include: municipal solid waste incineration, and rotary kiln incineration. For (concentrated) ODS refrigerants and blowing agents, approved technologies include: cement kilns, liquid injection incineration, gaseous/fume oxidation, reactor cracking, rotary kiln incineration, argon plasma arc, inductively coupled radio frequency plasma, microwave plasma, nitrogen plasma arc, gas phase catalytic dehalogenation, and superheated steam reactor.

This technology can process 250 kg of PU foam every 2 hours—or roughly 25 kg of CFC-11 (equivalent to 100 $MTCO_2eq$).

If C&D foam destruction with prior blowing agent recovery were to become widely practiced in California, there would be a market push for the establishment of additional processing facilities to handle the load. However, the construction of new facilities is not assessed quantitatively in this analysis; since this management option is assessed as a voluntary program rather than a regulatory one, any new construction would be driven by market demand, thereby implying cost-effectiveness. Assumptions of emissions and costs associated with transport, and blowing agent recovery and destruction are detailed in Section IV.6, below.

Various other management scenarios could be implemented to drive GHG emission reductions associated with the disposal of C&D foams. Depending on the type of construction foam and the recovery process employed, it could potentially be recovered manually and directly destroyed in a waste-to-energy (WTE) boiler, cement kiln, or blast furnace. However, these scenarios are not quantitatively assessed due to concerns about technical feasibility and lack of data. In particular, manual separation of foam from the steel could result in significant emissions of ODS/HFCs at large labor costs. In addition, any demolition load heavier than 30 tons would need to be held separately, either at the demolition site or at the combustion site, and this could incur additional storage, handling, and transportation costs. Moreover, if ODS-containing foams are co-incinerated in cement kilns, the chlorine content of the foam waste may be too high for safe operation of these facilities, if ODS feed rates are not carefully controlled. Finally, no emissions/costs data are available regarding the destruction of foam in a blast furnace. Section IV.9.3 provides additional qualitative information on these alternative options. (Caleb 2010)

IV.6. Key Assumptions

IV.6.1. General Assumptions

Transport

All PU panel foam that is recovered and handled at appliance recycling facilities is assumed to be transported by truck with an average fuel efficiency of 8.3 mpg.[85] These trucks are assumed to travel 50 miles beyond the transport required in the baseline to reach the appliance recycling facilities, which is consistent with the transport estimates developed for the appliance LCA. For developing transport emissions estimates, it is assumed that each truck has a foam carrying capacity of 6,600 lbs, which would contain approximately 500 lbs. of blowing agent.[86] In addition, it is assumed that trucks containing approximately 9,600 lbs. of recovered blowing agent would travel 750 miles to a destruction facility. These assumptions are also consistent with the appliance LCA.

Energy Consumption for Foam Processing

In the BAU, it is assumed that the energy consumed during the shredding of PU foam from panels prior to landfilling is similar to that required to shred appliance foam (0.06 kWh/unit). Thus, it is assumed that the shredding of foam panels in the BAU consumes approximately 6.3 kWh/MT foam, equivalent to 85 kWh per MT blowing agent.

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[85] Fuel Efficiency is based on the U.S. EPA Physical Emissions Rate Estimator Model for Heavy-Duty Vehicles (PERE-HD) Calculator (EPA 2010), and is consistent with the fuel efficiency for transporting whole appliances in the appliance end-of-life LCA.

[86] Truck carrying capacity is assumed to be equal to that for full appliances in the appliance LCA.

In the alternative management scenario, separation of foam panels from other C&D waste is assumed to be done manually, requiring negligible (if any) incremental energy consumption. Once at the appliance recycler, energy consumption associated with the recovery of blowing agent (prior to destruction at an approved facility) is estimated at 1,833 kWh per MT foam, or 24.8 kWh per kg blowing agent, using appliances data as a proxy.

Energy Consumption for Foam Blowing Agent Destruction

This analysis does not quantify the energy consumption required to destroy blowing agent using approved technologies, as such consumption is believed to be negligible (given that blowing agent destruction is likely to represent a minute percentage of a destruction facility's [e.g., cement kiln's] input feed on any given day, and that the facility is likely to operate regardless of whether blowing agent is destroyed or not [World Bank 2009]).[87] Therefore, the costs and GHG emissions associated with the energy consumed for refrigerant destruction are not quantified in this analysis.

IV.6.2. Assumptions for Calculating Emissions

Direct Foam Emissions (ODS and HFCs)

Direct emissions of ODS/HFC blowing agent from construction foam at EOL depend on the method of recovery, separation, and destruction. Baseline emission assumptions regarding foam blowing agent emissions are based on those developed for the appliance end-of-life LCA (see Section I.5.2). Specifically, PU panel foam is typically shredded prior to being disposed in landfills, resulting in losses of 24%. Once at a landfill, shredded foam is assumed to be compacted, resulting in further losses of 19%. In the baseline, it is further assumed that 20% of panels are directly landfilled, resulting in compaction emissions of 19%. Emissions of blowing agent may be reduced in landfills through bioremediation, sorption, and/or combustion in landfill gas boilers.

In the alternative management scenario, in which blowing agent is recovered from panels at appliance recycling facilities and subsequently destroyed using approved technologies, approximately 10% of blowing agent is assumed to be released during the foam recovery process (Caleb 2010), and an additional 0.01% is assumed to be released during destruction of the blowing agent.[88]

Table IV-3 presents estimated foam blowing agent emissions in the BAU and alternative management scenarios. As shown, the direct landfilling scenario is assumed to produce blowing agent emissions of only 19% to 27%, due to bioremediation, sorption, and/or combustion in landfills; as a result, the alternative management scenario is only assumed to avoid between 9% and 17% of blowing agent emissions. Depending on real-world landfill conditions and actual emissions avoided through bioremediation, sorption, and/or combustion, the environmental benefits associated with the alternative management scenario may be understated.

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[87] In the United States, only one of the 10 to 20 known destruction facilities that accept refrigerants for commercial destruction operates exclusively for the purpose of destroying refrigerants and other ODS. This facility is located in Ohio, thousands of miles from the California market.

[88] Blowing agent recovered from foam is likely to be destroyed at a minimum DRE of 99.99% (e.g., if it is destroyed in a rotary kiln): if blowing agent is destroyed in a PCB (hazardous waste-permitted) rotary kiln incinerator, the DRE will be 99.9999%.

Table IV-3: Emissions of Blowing Agent at EOL

Blowing Agent	BAU							Alternative Scenario
	Shredding/Landfilling (80%)				Direct Landfilling (20%)			Blowing Agent Recovery and Destruction
	Shredding	Compaction	In Landfill	Total	Compaction	In Landfill	Total	
CFC-11	24%	19%	0.3%	43%	19%	0.5%	19%	10%
HCFC-141b	24%	19%	1.7%	45%	19%	2.3%	21%	10%
HFC-245fa	24%	19%	5.7%	49%	19%	8.1%	27%	10%

For consistency with California's GHG emissions and reductions goals set by AB 32, this analysis uses GWP values from the Intergovernmental Panel on Climate Change (IPCC) 1995 Second Assessment Report (SAR) where possible. For those blowing agents with GWP values not reported in the SAR (i.e., HCFC-141b and HFC-245fa), this analysis uses GWP values from the IPCC 2001 Third Assessment Report (TAR). Table IV-4 presents each foam-blowing agent's ODP and GWP values used in this analysis.

Table IV-4: Blowing Agent ODPs and GWPs

Blowing Agent	Ozone Depleting Potential (ODP)[a]	GWP
CFC-11	1.0	3,800 [b]
HCFC-141b	0.12	700 [c]
HFC-245fa	0	950 [c]

[a] ODP values are from the WMO (2007).
[b] GWP based on SAR (IPCC 1995).
[c] GWP based on TAR (IPCC 2001).

GHG and Criteria Pollutant Emissions from Transport

The GHG and criteria pollutant emissions associated with additional transport required for the alternative management scenario is quantified in this analysis. Diesel fuel is assumed to have a lower heating value (LHV) of 135.5 MJ/gal and a CO_2eq emission factor of 94.7 g CO_2eq/MJ, based on GREET 1.8b used for the California Low Carbon Fuel Standard (ARB 2009).[89] Based on a truckload carrying 33,000 lbs. of C&D panels (including 500 lbs. of blowing agent contained within 6,600 lbs. of foam), and a fuel efficiency of 8.3 miles per gallon (mpg), the GHG emission factor for transport is 0.0068 kg CO_2eq per truck trip distance per kg blowing agent. Similarly, for the transport of blowing agent to a destruction facility, a GHG emission factor of 0.0035 kg CO_2eq per truck trip distance per kg blowing agent is assumed, based on a truckload carrying 12,000 lbs.[90] and a fuel efficiency of 8.3 mpg. In addition, criteria pollutant emissions from transport are assumed to be consistent with those from the appliance end-of-life LCA.[91] Therefore, based on a 50-mile truck trip to appliance recycling facilities and a 750 mile trip to destruction facilities, Table IV-5 presents the assumed emissions per kg blowing agent.

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[89] The CO_2eq emission factor for diesel fuel includes well to tank (WTT) and tank-to-wheel energy and greenhouse gas values and vehicle fuel emissions for California Ultra Low-Sulfur Diesel (ULSD).

[90] Including 9,600 lbs. of blowing agent contained in twelve 1,000-lb. cylinders.

[91] Criteria pollutant emissions associated with transport are based on the emission factors developed from Façanha and Horvath (2007). It should be noted that criteria air pollutant emission factors reflect global emission estimates; due to analytical limitations, emissions for criteria air pollutants could not be disaggregated for California specific regions or air districts.

Table IV-5: GHG and Criteria Pollutant Transport Emission Factors (Emissions/kg blowing agent)

Emissions Factor	Incremental Transport to Appliance Recycling Facility	Incremental Transport to Destruction Facility	Total Incremental Transport in Management Scenario
GHG (g CO_2eq/kg blowing agent)	340.12	265.72	605.84
NO_x (g/kg blowing agent)	7.97	2.26	10.24
PM10 (g/kg blowing agent)	0.22	0.06	0.28
PM2.5 (g/kg blowing agent)	0.04	0.01	0.05
SO_2 (g/kg blowing agent)	0.20	0.06	0.26

GHG and Criteria Pollutant Emissions from Energy Consumption

Table IV-6 presents the emission factors used to calculate indirect GHG and criteria pollutant emissions associated with the energy consumption used for foam processing (i.e., foam shredding and blowing agent recovery in a fully-automated/enclosed system) in the alternative management scenario. These emission factors are the same as those used in the appliance LCA.

Table IV-6: Emission Factors Associated with Energy Consumption for Foam Processing (Alternative Management Scenario)

Energy Consumption Emission Factors (g/kWh)				
g CO_2eq/kWh[a]	g NO_x/kWh	g PM10/kWh	g PM2.5/kWh	g SO_x/kWh
751.50	1.18	1.02	0.27	2.60

[a] The CO_2eq emission factor represents net CO_2, which includes CO_2, CO, and VOCs.
Source: GREET 1.8c.

Based on the estimated 6.3 kWh/MT required to shred panel foam and the 24.8 kWh/kg required to recover the blowing agent from the foam matrix using a fully automated system, the GHG and criteria pollutant emissions associated with foam processing in the alternative management scenario are shown in Table IV-7.

Table IV-7: Emissions Associated with Energy Consumption During Foam Shredding and Blowing Agent Recovery

Foam Processing Activity	Kg Emission				
	GHG	NO_x	PM10	PM2.5	SO_x
Foam Shredding (per MT of foam)	4.7[a]	0.0074	0.0064	0.0017	0.016
Blowing Agent Recovery (per kg of blowing agent)	18.6[a]	0.029	0.025	0.0068	0.064

[a] The CO_2eq emission factor represents net CO_2, which includes CO_2, CO, and VOCs.

IV.6.3. Assumptions for Calculating Costs

Foam Handling Costs

TEAP (2009) provides global average cost estimates for various processes of EOL treatment of sandwich panels—assuming prior recovery of blowing agent—in both densely and sparsely populated areas. These costs include segregation/collection, transport for destruction, recovery processing, and destruction. This analysis applies the mid-range costs for densely populated areas, assuming that C&D foam recovery and destruction will occur primarily in those areas where it is most cost-effective. These estimated costs are presented in Table IV-8 on a per-kg blowing agent basis. As shown below, the total cost of segregating, transporting, recovering, and destroying blowing agent from foam panels under the management scenario would be approximately $146 per kg foam blowing agent. It should be underscored that the costs of C&D foam panel recovery and treatment without prior blowing agent recovery would be lower than those shown here–by an estimated $35/kg (BING 2008). Transport and destruction costs for destroying whole foam in a WTE or blast furnace without prior blowing agent recovery could also be lower, although segregation/collection costs could be higher if the foam were to be manually separated from steel-facing panels.

Table IV-8: Assumed Average Costs for EOL Treatment of Foam Panels [a]

Activity	Estimated Costs Per Unit of Blowing Agent	
	Per Kilogram	Per Pound
Segregation/Collection	$83	$37
Transport	$22[b]	$10
Recovery Processing	$35	$16
Destruction	$6	$3
Total	$146	$66

[a] Source: TEAP (2009).

[b] Transport costs in TEAP (2009) are estimated at $8/kg blowing agent, and assume a truck trip of 30 miles. In this analysis, transport is assumed to include a 50-mile trip to an appliance recycling facility, as well as a 750-mile trip to transport recovered blowing agent to a destruction facility. Transport costs have been scaled up to reflect this additional transport relative to TEAP estimates.

It is assumed that in the baseline, all foam panels would be transported to landfills along with the rest of the C&D waste. This transport is assumed to be similar to the transport required to landfill foam fluff in the alternative management scenario (post-blowing agent recovery). Therefore, all costs presented above are incremental to the baseline.

Foam Shredding Costs: Labor and Energy

In the BAU, 80% of PU panels are shredded prior to being landfilled along with other C&D waste. It is assumed that this process will require the same energy as when shredding appliance foam. Labor and energy consumption costs for appliance foam shredding are approximately $0.16 per unit, or $0.01 per lb. of foam, based on a labor rate of $40/hr (ARB 2009b) and an average electricity cost of $0.11/kWh (EIA 2010). Energy consumption costs are therefore estimated at approximately $16.40/MT foam, equivalent to $0.22 per kg blowing agent.

Foam Disposal Costs

In the baseline, foam is assumed to be landfilled with the rest of the C&D waste at a landfill tipping fee of $65/ton material,[92] which is consistent with the appliance LCA. In the management scenario, foam fluff is assumed to be landfilled (following blowing agent recovery) at the same $65/ton tipping fee.

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[92] Direct communication with Republic Waste Services indicated average tipping fees of $50-100/tonne (August 4, 2010). Anecdotal evidence suggests average may be closer to the low end of this range.

IV.7. Discussion of Findings

IV.7.1. Cost Assessment

Based on the cost assumptions presented above, Table IV-9 presents estimated BAU costs associated with the disposal of ODS and HFC foam panels in 2010 through 2050. Net present value (NPV) costs are calculated based on a discounting rate of 5%.

Under the alternative management scenario, the additional costs associated with foam processing are slightly offset by the reduced foam shredding costs, and slightly lower landfill tipping fees. Table IV-10 and Table IV-11 present the costs by activity incurred in the management scenario. Net present value (NPV) costs are calculated based on a discounting rate of 5%. Table IV-12 presents the total incremental costs associated with varying levels of adoption of the alternative management approach of 25% and 50%.

Table IV-9: Total Costs in BAU ($)

Year	Foam Shredding			Foam Landfilling			Total BAU		
	ODS	HFC	Total	ODS	HFC	Total	ODS	HFC	Total
2010	$0	$0	$0	$0	$0	$0	$0	$0	$0
2015	$0	$0	$0	$0	$0	$0	$0	$0	$0
2020	$258	$0	$258	$1,278	$0	$1,278	$1,536	$0	$1,536
2025	$723	$0	$723	$3,578	$0	$3,578	$4,301	$0	$4,301
2030	$16,236	$0	$16,236	$80,411	$0	$80,411	$96,647	$0	$96,647
2035	$3,407	$10,221	$13,629	$16,874	$50,622	$67,497	$20,281	$60,844	$81,125
2040	$0	$45,569	$45,569	$0	$225,682	$225,682	$0	$271,251	$271,251
2045	$0	$83,798	$83,798	$0	$415,013	$415,013	$0	$498,810	$498,810
2050	$0	$118,321	$118,321	$0	$585,989	$585,989	$0	$704,310	$704,310
Total	$127,929	$1,109,700	$1,237,629	$633,572	$5,495,836	$6,129,408	$761,501	$6,605,536	$7,367,037
NPV	$49,160	$212,408	$261,568	$243,466	$1,051,962	$1,295,428	$292,626	$1,264,370	$1,556,996

Table IV-10: Costs by Activity in the Management Scenario (Part A)

Year	Separation/Collection			Transport			Recovery		
	ODS	HFC	Total	ODS	HFC	Total	ODS	HFC	Total
2010	$0	$0	$0	$0	$0	$0	$0	$0	$0
2015	$0	$0	$0	$0	$0	$0	$0	$0	$0
2020	$120,040	$0	$120,040	$32,397	$0	$32,397	$50,926	$0	$50,926
2025	$336,078	$0	$336,078	$90,703	$0	$90,703	$142,579	$0	$142,579
2030	$7,552,433	$0	$7,552,433	$2,038,297	$0	$2,038,297	$3,204,062	$0	$3,204,062
2035	$1,584,871	$4,754,612	$6,339,482	$427,735	$1,283,204	$1,710,938	$672,369	$2,017,108	$2,689,477
2040	$7,552,433	$21,196,768	$28,749,201	$2,038,297	$5,720,713	$7,759,010	$3,204,062	$8,992,568	$12,196,631
2045	$0	$38,979,258	$38,979,258	$0	$10,519,960	$10,519,960	$0	$16,536,655	$16,536,655
2050	$0	$55,037,936	$55,037,936	$0	$14,853,973	$14,853,973	$0	$23,349,427	$23,349,427
Total	$59,507,064	$516,185,833	$575,692,897	$16,060,129	$139,311,378	$155,371,507	$25,245,421	$218,987,929	$244,233,350
NPV	$22,867,092	$98,803,467	$121,670,559	$6,171,510	$26,665,682	$32,837,192	$9,701,191	$41,916,622	$51,617,813

Table IV-11: Costs by Activity in the Management Scenario (Part B)

Year	Destruction			Foamfluff Landfilling			Total Cost		
	ODS	HFC	Total	ODS	HFC	Total	ODS	HFC	Total
2010	$0	$0	$0	$0	$0	$0	$0	$0	$0
2015	$0	$0	$0	$0	$0	$0	$0	$0	$0
2020	$7,857	$0	$7,857	$1,183	$0	$1,183	$212,403	$0	$212,403
2025	$21,998	$0	$21,998	$3,313	$0	$3,313	$594,671	$0	$594,671
2030	$494,341	$0	$494,341	$74,460	$0	$74,460	$13,363,593	$0	$13,363,593
2035	$103,737	$311,211	$414,948	$15,625	$46,876	$62,502	$2,804,337	$8,413,010	$11,217,347
2040	$494,341	$1,387,425	$1,881,766	$74,460	$208,982	$283,442	$13,363,593	$37,506,456	$50,870,050
2045	$0	$2,551,370	$2,551,370	$0	$384,302	$384,302	$0	$68,971,543	$68,971,543
2050	$0	$3,602,483	$3,602,483	$0	$542,626	$542,626	$0	$97,386,446	$97,386,446
Total	$3,895,008	$33,786,709	$37,681,717	$586,688	$5,089,144	$5,675,832	$105,294,310	$913,360,993	$1,018,655,303
NPV	$1,496,755	$6,467,136	$7,963,891	$225,450	$974,116	$1,199,566	$40,461,998	$174,827,023	$215,289,021

Table IV-12: Total Incremental Costs in 25% and 50% Compliance with Management Scenario

Year	Management Scenario (25% Compliance)			Management Scenario (50% Compliance)		
	ODS	HFC	Total	ODS	HFC	Total
2010	$0	$0	$0	$0	$0	$0
2015	$0	$0	$0	$0	$0	$0
2020	$52,717	$0	$52,717	$105,434	$0	$105,434
2025	$147,592	$0	$147,592	$295,185	$0	$295,185
2030	$3,316,737	$0	$3,316,737	$6,633,473	$0	$6,633,473
2035	$696,014	$2,088,042	$2,784,055	$1,392,028	$4,176,083	$5,568,111
2040	$0	$9,308,801	$9,308,801	$0	$18,617,603	$18,617,603
2045	$0	$17,118,183	$17,118,183	$0	$34,236,366	$34,236,366
2050	$0	$24,170,534	$24,170,534	$0	$48,341,068	$48,341,068
Total	$26,133,202	$226,688,864	$252,822,066	$52,266,405	$453,377,728	$505,644,133
NPV	$10,042,343	$43,390,663	$53,433,006	$20,084,686	$86,781,327	$106,866,012

IV.7.2. Benefits Assessment

GHG Emissions Avoided

Table IV-13 presents the GHG emissions associated with C&D foam disposal in the baseline. BAU emissions are almost entirely due to direct blowing agent release during shredding and landfilling.

Table IV-13: GHG Emissions from C&D Foam Disposal in the BAU (MTCO$_2$eq)

Year	Direct (Foam) Emissions			Indirect Emissions from Energy and Transport			Total Emissions		
	ODS	HFC	Total	From Treatment of ODS Foam	From Treatment of HFC Foam	Total	ODS	HFC	Total
2010	—	—	—	—	—	—	—	—	—
2015	—	—	—	—	—	—	—	—	—
2020	2,132.6	—	2,132.6	0.1	—	0.1	2,132.7	—	2,132.7
2025	3,555.6	—	3,555.6	0.2	—	0.2	3,555.8	—	3,555.8
2030	25,627.5	—	25,627.5	4.7	—	4.7	25,632.2	—	25,632.2
2035	5,377.9	24,298.1	29,676.0	1.0	2.9	3.9	5,378.9	24,301.0	29,679.9
2040	—	108,324.5	108,324.5	—	13.1	13.1	—	108,337.6	108,337.6
2045	—	199,200.5	199,200.5	—	24.1	24.1	—	199,224.7	199,224.7
2050	—	281,267.2	281,267.2	—	34.1	34.1	—	281,301.3	281,301.3
Total	240,565.6	2,637,928.6	2,878,494.2	36.8	319.5	356.3	240,602.4	2,638,248.1	2,878,850.5

Table IV-14 and Table IV-15 present the emissions avoided assuming varying levels of compliance with the management scenario. As shown, significant emissions reductions result from foam blowing agent recovery and destruction in the management scenario. However, these GHG emission reductions are partially offset by increased emissions associated with transport and energy consumption for foam processing. By 2050, a 25% adoption rate is estimated to result in 0.52 million MTCO$_2$eq reduced, while a 50% adoption rate results in 1.04 million MTCO$_2$eq reduced. Avoided emissions of HFCs are zero through 2030 as there are no HFCs projected to reach EOL in building foams until 2031.

Table IV-14: GHG Emissions Avoided in Alternative Management Scenario (MTCO$_2$eq), Assuming 25% Adoption

Year	Direct (Foam) Emissions Avoided			Indirect Emissions Avoided from Energy and Transport[a]			Total Emissions Avoided		
	ODS	HFCs	Total	To Process ODS Units	To Process HFC Units	Total	To Process ODS Units	To Process HFC Units	Total
2010	0	0	0	0	0	0	0	0	0
2015	0	0	0	0	0	0	0	0	0
2020	395	0	395	-7	0	-7	388	0	388
2025	660	0	660	-20	0	-20	640	0	640
2030	4,803	0	4,803	-439	0	-439	4,364	0	4,364
2035	1,008	4,704	5,712	-92	-276	-368	916	4,428	5,344
2040	0	20,973	20,973	0	-1,232	-1,232	0	19,741	19,741
2045	0	38,568	38,568	0	-2,265	-2,265	0	36,303	36,303
2050	0	54,457	54,457	0	-3,198	-3,198	0	51,259	51,259
2010–2020	1,079	0	1,079	-19	0	-19	1,060	0	1,060
2010–2050	44,978	510,735	555,713	-3,457	-29,990	-33,448	41,521	480,744	522,265

Table IV-15: GHG Emissions Avoided in Alternative Management Scenario (MTCO$_2$eq), Assuming 50% Adoption

Year	Direct (Foam) Emissions Avoided			Indirect Emissions Avoided from Energy and Transport[a]			Total Emissions Avoided		
	ODS	HFCs	Total	To Process ODS Units	To Process HFC Units	Total	To Process ODS Units	To Process HFC Units	Total
2010	0	0	0	0	0	0	0	0	0
2015	0	0	0	0	0	0	0	0	0
2020	790	0	790	-14	0	-14	776	0	776
2025	1,319	0	1,319	-39	0	-39	1,280	0	1,280
2030	9,606	0	9,606	-878	0	-878	8,729	0	8,729
2035	2,016	9,409	11,425	-184	-552	-737	1,832	8,856	10,688
2040	0	41,946	41,946	0	-2,463	-2,463	0	39,483	39,483
2045	0	77,135	77,135	0	-4,529	-4,529	0	72,606	72,606
2050	0	108,913	108,913	0	-6,395	-6,395	0	102,518	102,518
2010–2020	2,158	0	2,158	-38	0	-38	2,120	0	2,120
2010–2050	89,956	1,021,469	1,111,425	-6,915	-59,981	-66,895	83,041	961,489	1,044,530

Figure IV-2 and Figure IV-3 present the cumulative and annual net GHG emissions avoided (MTCO$_2$eq) from 2010-2050, for both levels of compliance with the management scenario, respectively.

Figure IV-2: Cumulative Net GHG Emissions Avoided (MTCO$_2$eq) 2010-2050

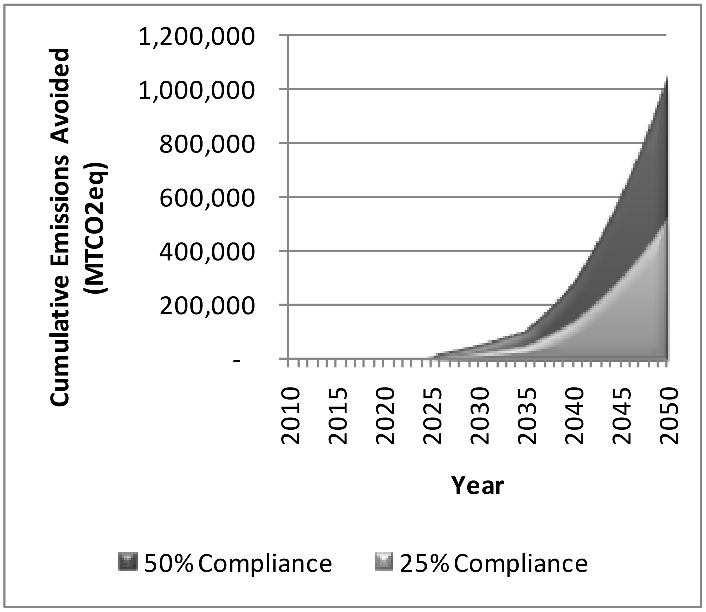
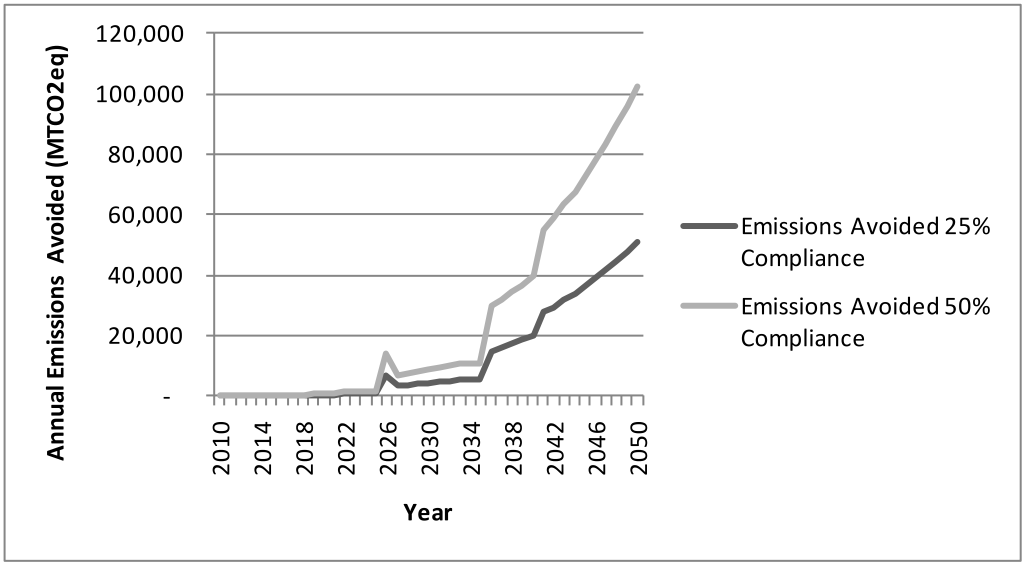


Figure IV-3: Total Annual GHG Emissions Avoided (MTCO$_2$eq) 2010-2050



ODS Emissions Avoided

Baseline ODS emissions are incurred from 2016 through 2035, after which point all ODS PU panel foam is assumed to have reached EOL. Table IV-16 presents ODS emissions avoided by adopting the alternative management scenario through 2035.

Table IV-16: ODS Emissions Avoided in Alternative Management Scenario ($MTCO_2eq$), Assuming 25% and 50% Adoption

Year	ODS Emissions Avoided (ODP weighted tons)	
	25% Adoption	50% Adoption
2010	—	—
2015	—	—
2020	0.1	0.2
2025	0.2	0.3
2030	0.8	1.5
2035	0.2	0.3
2040	—	—
2045	—	—
2050	—	—
2010–2020	0.3	0.6
2010–2050	8.0	16.0

Criteria Pollutant Emissions

Criteria pollutant emissions result from transport and energy consumption during foam shredding and blowing agent recovery. Table IV-17 presents the net incremental criteria pollutant emissions resulting from both 25% and 50% compliance with the alternative management scenario.

Table IV-17: Criteria Pollutant Incremental Emissions (MT)

Year	25% Compliance				50% Compliance			
	NOx	PM10	PM2.5	SOx	NOx	PM10	PM2.5	SOx
2010	—	—	—	—	—	—	—	—
2015	—	—	—	—	—	—	—	—
2020	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2025	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.1
2030	0.9	0.6	0.2	1.5	1.8	1.2	0.3	3.0
2035	0.8	0.5	0.1	1.3	1.5	1.0	0.3	2.5
2040	2.5	1.7	0.4	4.2	5.1	3.3	0.9	8.3
2045	4.7	3.1	0.8	7.7	9.3	6.1	1.6	15.3
2050	6.6	4.3	1.1	10.9	13.2	8.6	2.3	21.7
Total	69.1	45.2	12.0	113.9	137.6	89.8	23.9	226.5

IV.7.3. Cost Effectiveness

The alternative management scenario can be implemented at a net cost of $102 per $MTCO_2eq$ reduced. Costs are not incurred until 2016, when ODS PU panels are assumed to begin reaching EOL. Table IV-18 presents the cost effectiveness of implementing the management scenario. Because cost effectiveness is evaluated on a per $MTCO_2eq$ reduced basis, results do not vary by adoption rate.

Table IV-18: Cost Effectiveness ($/MTCO$_2$eq)[a]

	25% Compliance			50% Compliance		
	ODS	HFC	Total	ODS	HFC	Total
NPV Costs 2010-2050 ($ million)	$10.0	$43.4	$53.4	$20.1	$86.8	$106.9
Emissions Avoided 2010-2050 (MMTCO$_2$eq)	0.04	0.48	0.52	0.08	0.96	1.04
Cost Effectiveness ($/MTCO$_2$eq)	$242	$90	$102	$242	$90	$102

[a] Costs are in present value (at 5% discount rate).

It should be underscored that the cost effectiveness results presented above assume bioremediation, sorption, and combustion of gases in landfills, which significantly reduce emissions in the BAU. If these BAU emissions reductions were not included, more emissions would be avoided in the management scenario, resulting in a lower cost per MTCO$_2$eq avoided. Indeed, if baseline emissions avoided in landfills were assumed to be zero, the NPV cost effectiveness from 2010-2050 would be $76/MTCO$_2$eq for ODS, $33 for HFC, and $37 for ODS/HFCs combined.

IV.8. Recommendations

Approximately 1.0 MMTCO$_2$eq is estimated to be avoidable by 2050 through the recovery and destruction of steel-faced foam panels from demolished buildings in CA, assuming a 50% participation rate. ODS emission reductions peak at 0.01 MMTCO$_2$eq in 2030 and are expected to be obsolete in buildings by 2036. Emission reductions are relatively small because ODS-containing foam panels were not used until the 1980s, and the first year they are expected to reach EOL is 2016. HFC-containing panels were not used until the 2000s, and are not expected to reach EOL in CA buildings until 2031. However, it must be underscored that an optimistic scenario for BAU landfill conditions is applied in this analysis (assuming bioremediation, sorption, and combustion of gases in landfills), which significantly reduce emissions in the BAU; if these BAU emissions reductions were not included, HFC emission reductions by 2050 would be 2.6 MMTCO$_2$eq at only $33/MTCO$_2$eq. Moreover, pending additional research and development, other types of building foam may become technically and economically recoverable in CA. Given that panel foam accounts for only an estimated 10% of building foam in CA, this could result in significant additional GHG savings over the long-term. Additional research is needed to assess the infrastructure needed to support the alternative management scenario explored in this analysis, as well as other pathways and methods of building foam recovery/ destruction in California.

IV.9. Additional Considerations

Due to the limited scope of this research project, a number of simplifications were made in this analysis. A more complete LCA would require additional considerations and a more nuanced methodology. In particular, the following key considerations, described in further detail below, will affect the cost-effectiveness of C&D foam recovery and destruction: the assumed emissions avoided in the baseline (landfill) scenario; the capital costs considered within the boundary of the analysis; the processes/technologies used to recover and destroy C&D foam; and the types of C&D foam recovered for destruction.

IV.9.1. Landfill Emissions Avoided

To ensure consistency with Climate Action Reserve ODS Destruction Protocol, this analysis assumes significant emission reductions occur in landfills due to bioremediation, sorption, and combustion of landfill gases in the project baseline. (CAR. 2010) However, it is uncertain to what extent landfills actually reduce emissions of ODS foam-blowing agent. Caleb (2010) notes that there is limited evidence to suggest that anaerobic conditions can develop in hazardous waste cells currently, and that methanogenic bacteria are unlikely to be present in large numbers in a hazardous waste landfill. Without these conditions, bioremediation cannot occur. To ensure ideal landfill conditions, landfills could practice managed attenuation, which would involve mixing the anaerobic waste with the foam to encourage microbial destruction of CFCs. In addition, it is unclear if sorption and the combustion of landfill gases significantly reduces emission of ODS and HFCs from landfills. Limited studies of actual landfill activities have been conducted to date, and the data from which the assumptions of avoided emissions are developed are based primarily on laboratory studies. As stated above, if baseline landfill emissions avoided were assumed to be zero for all blowing agent types, the cost effectiveness of foam recovery and destruction from C&D foam panels becomes more favorable, changing from \$242 to \$76 per $MTCO_2eq$ for ODS; from \$90 to \$33 per $MTCO_2eq$ for HFCs; and from \$102 to \$37 per $MTCO_2eq$ for both ODS and HFCs combined.

Additional research is recommended to measure high-GWP GHG emissions from landfilled waste foam and the potential emission reductions that take place due to attenuation, sorption, and combustion within the landfill.

IV.9.2. Capital Costs

Capital costs of equipment purchase and facility rental are not included in this analysis, as it is assumed that any additional capital costs necessary to expand this type of voluntary program would be incurred only if viable/ cost-effective. However, if C&D foam recovery and destruction were to be mandated, such costs would be important to quantitatively consider. The cost of installing the types of blowing agent recovery technologies used in Europe is estimated at \$520,000 per system. In addition, C&D foam processing facilities would require approximately 465 m^2 space, and two operators per shift. Such a facility could handle both panel and non-panel C&D foam; however, because non-panel C&D foams do not contain metal, which have a high market value on the recycled market, processing these other types of foams would be less cost-effective. (Caleb 2010)

IV.9.3. Alternative C&D Foam Treatment

This analysis only considers the recovery and handling of PU panel foam with prior blowing agent recovery. Other recovery options may be available that could reduce costs of handling. For instance, PU panels could be sent directly to WTE facilities in the state for destruction without prior blowing agent recovery. However, given the limited capacity of WTE facilities in CA, it is unclear whether or not this option is feasible. Alternatively, ODS/HFC-containing foam could be co-incinerated in cement kilns. However, the chlorine content of ODS-containing foam waste may be too high for these facilities, if ODS feed rates are not carefully controlled, and the supply of foam waste materials may not be consistent enough to warrant processing them. (Caleb 2010)

In addition, there has been limited experience in the United Kingdom and Germany with destruction of C&D foam panels by blast furnace. Specifically, large panel sections have been put into blast furnaces with the steel recovered and the foam contributing to the fuel. The blowing agents are destroyed at the high temperatures used, ensuring good destruction efficiency. In these countries, the producers of foam panels were subsidiaries of steel companies, making this closed loop process easy to launch. This option may represent the most cost-effective option. (Jeffs 2011)

IV.9.4. Other Types of C&D Foam

This analysis only considers the recovery and disposal of PU panel foam from construction and demolition sites. Given current infrastructure and technical barriers, the recovery and destruction of other types of C&D foam is assumed to not be feasible. Although the costs of recovery have been estimated to be prohibitive for these other foam types (approximately $300/MTCO2e reduction), considering the technical difficulty of foam separation and processing (BRE 2010, as reported in Caleb 2010), additional research is needed to further assess costs and emissions associated with the recovery of these foams in California.

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IV.11. Appendix A: Report Figures presented as Data

The following tables show the data which ICF used to develop the figures and graphs presented in Part IV. LCA on Construction and Demolition (C&D) Foam. In each case, numbered tables are followed by a figure reference in brackets (e.g., from Figure IV-xx), and the title of the relevant figure as it is shown in the body of the report.

Table IV-19 (from Figure IV-1): Total Banks in Building and Waste Streams

Year	Total in Buildings			Banks in Waste Streams		
	CFCs	HCFCs	HFCs	CFCs	HCFCs	HFCs
1960	0.00	0.00	0.00	0.00	0.00	0.00
1961	3.74	0.00	0.00	0.00	0.00	0.00
1962	7.63	0.00	0.00	0.00	0.00	0.00
1963	11.68	0.00	0.00	0.00	0.00	0.00
1964	15.89	0.00	0.00	0.00	0.00	0.00
1965	20.28	0.00	0.00	0.00	0.00	0.00
1966	24.86	0.00	0.00	0.00	0.00	0.00
1967	29.65	0.00	0.00	0.00	0.00	0.00
1968	34.65	0.00	0.00	0.00	0.00	0.00
1969	39.89	0.00	0.00	0.00	0.00	0.00
1970	45.38	0.00	0.00	0.00	0.00	0.00
1971	50.75	0.00	0.00	0.00	0.00	0.00
1972	56.39	0.00	0.00	0.00	0.00	0.00
1973	62.32	0.00	0.00	0.00	0.00	0.00
1974	68.54	0.00	0.00	0.00	0.00	0.00
1975	75.09	0.00	0.00	0.00	0.00	0.00
1976	81.98	0.00	0.00	0.00	0.00	0.00
1977	89.24	0.00	0.00	0.00	0.00	0.00
1978	96.90	0.00	0.00	0.00	0.00	0.00
1979	104.97	0.00	0.00	0.00	0.00	0.00
1980	113.48	0.00	0.00	0.00	0.00	0.00
1981	122.01	0.00	0.00	0.00	0.00	0.00
1982	131.04	0.00	0.00	0.00	0.00	0.00
1983	140.60	0.00	0.00	0.00	0.00	0.00
1984	150.73	0.00	0.00	0.00	0.00	0.00
1985	161.46	0.00	0.00	0.00	0.00	0.00
1986	172.88	0.00	0.00	0.00	0.00	0.00
1987	185.00	0.00	0.00	0.00	0.00	0.00
1988	197.85	0.00	0.00	0.00	0.00	0.00
1989	211.49	0.00	0.00	0.00	0.00	0.00
1990	225.97	0.00	0.00	0.00	0.00	0.00

Year	Total in Buildings			Banks in Waste Streams		
	CFCs	HCFCs	HFCs	CFCs	HCFCs	HFCs
1991	240.68	0.00	0.00	2.35	0.00	0.00
1992	253.27	0.00	0.00	4.73	0.00	0.00
1993	266.69	0.00	0.00	7.15	0.00	0.00
1994	276.16	0.80	0.00	9.61	0.00	0.00
1995	281.17	2.49	0.00	12.12	0.00	0.00
1996	281.15	5.16	0.00	14.69	0.00	0.00
1997	275.52	8.94	0.00	17.32	0.00	0.00
1998	269.73	12.93	0.00	20.02	0.00	0.00
1999	263.78	17.14	0.00	22.81	0.00	0.00
2000	257.66	21.60	0.00	25.68	0.00	0.00
2001	251.35	25.93	0.19	28.41	0.00	0.00
2002	245.14	30.04	0.63	31.24	0.00	0.00
2003	238.74	34.03	1.50	34.18	0.00	0.00
2004	232.12	36.95	2.21	37.25	0.00	0.00
2005	225.27	39.52	2.77	40.44	0.00	0.00
2006	218.17	41.54	3.59	43.77	0.00	0.00
2007	210.81	43.68	4.47	47.25	0.00	0.00
2008	203.17	45.95	5.40	50.90	0.00	0.00
2009	195.22	47.67	6.81	54.72	0.00	0.00
2010	186.95	48.03	9.22	58.74	0.00	0.00
2011	178.33	47.65	12.46	62.66	0.00	0.00
2012	169.73	47.28	15.87	66.79	0.00	0.00
2013	160.73	46.90	19.48	71.15	0.00	0.00
2014	151.32	46.53	23.30	75.75	0.00	0.00
2015	141.47	46.17	27.34	80.61	0.00	0.00
2016	131.14	45.81	31.62	85.76	0.00	0.00
2017	120.30	45.45	36.15	91.22	0.00	0.00
2018	108.91	45.09	40.96	97.01	0.00	0.00
2019	96.95	44.74	46.05	103.15	0.00	0.00
2020	84.37	44.38	51.46	109.66	0.00	0.00

Table IV-20 (from Figure IV-2): Cumulative Net GHG Emissions Avoided (MTCO2eq) 2010–2050

Year	25% Compliance	50% Compliance
2010	—	—
2011	—	—
2012	—	—
2013	—	—
2014	—	—
2015	—	—
2016	58	116
2017	183	365
2018	384	768
2019	672	1,344
2020	1,060	2,120
2021	1,546	3,092
2022	2,156	4,312
2023	2,906	5,813
2024	3,628	7,256
2025	4,268	8,536
2026	11,268	22,536
2027	14,774	29,548
2028	18,545	37,091
2029	22,602	45,205
2030	26,967	53,934
2031	31,659	63,318
2032	36,763	73,526
2033	42,153	84,307
2034	47,513	95,026
2035	52,857	105,714
2036	67,761	135,521
2037	83,748	167,497
2038	100,900	201,800
2039	119,300	238,601
2040	139,042	278,084
2041	166,608	333,216
2042	196,136	392,272
2043	227,768	455,536
2044	261,654	523,309
2045	297,957	595,914
2046	336,851	673,701
2047	378,521	757,042
2048	423,168	846,336
2049	471,006	942,012
2050	522,265	1,044,530

Table IV-21 (from Figure IV-3): Total Annual GHG Emissions Avoided (MTCO2eq) 2010-2050

Year	25% Compliance	50% Compliance
2010	—	—
2011	—	—
2012	—	—
2013	—	—
2014	—	—
2015	—	—
2016	58	116
2017	125	249
2018	201	402
2019	288	577
2020	388	776
2021	486	972
2022	610	1,220
2023	750	1,501
2024	722	1,443
2025	640	1,280
2026	7,000	14,000
2027	3,506	7,012
2028	3,771	7,543
2029	4,057	8,114
2030	4,364	8,729
2031	4,692	9,384
2032	5,104	10,208
2033	5,390	10,780
2034	5,360	10,720
2035	5,344	10,688
2036	14,904	29,807
2037	15,988	31,975
2038	17,151	34,303
2039	18,401	36,801
2040	19,741	39,483
2041	27,566	55,132
2042	29,528	59,057
2043	31,632	63,263
2044	33,886	67,773
2045	36,303	72,606
2046	38,893	77,787
2047	41,670	83,341
2048	44,647	89,294
2049	47,838	95,676
2050	51,259	102,518

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V. LCA on Fire Extinguishing Agents and Other Miscellaneous ODS / High-GWP Chemicals

V.1. Introduction

As part of the California Air Resources Board's (CARB's) responsibilities under AB 32, the agency sponsored projects focused on developing an inventory of greenhouse gases (GHGs) in California. To that end, CARB contracted the Institute for Research and Technical Assistance (IRTA) to develop bottom up estimates of emissions of GHGs for 2010 and 2020 for fire protection (total flooding and streaming applications), solvents (including film cleaning, vapor degreasing and disk lubing),[93] and other applications—namely stockpiles of CFC and an HCFC used in dry cleaning of delicate garments and costumes in the movie industry, use of inert material in implantable devices by medical device manufacturers, and cleaning of energized electrical equipment. IRTA undertook the study by relying on local air district permits and information from equipment installers and suppliers to generate emission estimates for solvents and fire protection equipment and the bank of agents in fire protection equipment. The results indicate that emissions will decline in all three of the applications that were analyzed over the period because of trends already underway. The study estimates high-global warming potential (GWP) banks in the fire protection sector to total 160,512 metric tons of carbon dioxide equivalent ($MTCO_2eq$) in 2010, and 88,570 $MTCO_2eq$ in 2020; high-GWP banks of stockpiled ODS solvents were estimated at 17,847 $MTCO_2eq$ in 2010. (IRTA 2011)

V.2. Purpose

This lifecycle analysis assesses potential emission reductions and costs associated with the proper management (i.e., recovery and subsequent reclamation or destruction) of high-GWP gases banked in the fire protection sector and miscellaneous solvent stockpiles, as estimated by IRTA (2011). Specifically, the analysis quantifies the potential direct GHG emission savings and indirect CO_2 and criteria air pollutant emission savings associated with recovery and reclamation/destruction of such high-GWP chemicals, as well as the incremental costs per $MTCO_2eq$ reduced.

V.3. Background

The fire protection sector consists of two segments: (1) fixed total flooding systems used to protect expensive electronics equipment and data that can be destroyed in the event of a fire; and (2) portable fire extinguishers used for local fire protection (e.g., in marine and aerospace facilities). The high-GWP fire extinguishing agents used in these applications include halons (halon 1301 and halon 1211), a blend containing HCFC-123 (Halotron I), HFCs (HFC-227ea and HFC-125), and perfluorocarbons (PFCs). The GWPs and ozone-depleting potential (ODPs) of these chemicals are presented below.

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[93] In film cleaning, one HCFC and hydrofluoroethers (HFEs) are used by the movie industry to clean original negative and archived film during processing to remove fingerprints and particle contaminants. In vapor degreasing, an HCFC, HFEs and HFC solvents and their blends are used to remove various contaminants like oils, flux and particles from metal and plastic parts in general and precision cleaning. In disk lubing, perfluorocarbon (PFC) and HFE solvents act as carriers for a lubricant which is deposited on hard computer disks. (IRTA 2011)

Table V-1: GWPs and ODPs of Fire Extinguishing Agents Banked in California

Chemical	GWP	ODP
Halon 1301	6,900	10
Halon 1211	1,300	3
Halotron I	205	0.0186
PFC	6,750	0
HFC-227ea	2,900	0
HFC-125	2,800	0
HFC-236	6,300	0

IRTA (2011) estimated the banks of these chemicals installed in 2010 and projected in 2020 assuming business-as-usual (BAU) for both total flooding and streaming equipment in California, as presented in Table V-2.

Table V-2: Bank of High-GWP Gases in Fire Protection Sector in California (IRTA 2011)

Sector	System Type	Bank Size (lbs)		Bank Size (MTCO2 eq.)	
		2010	2020	2010	2020
Fire Protection: Flooding Agents	Halon 1301	300,000	0	939,201	0
	HFC-227ea	1,350,000	1,080,000	1,776,316	1,421,053
	HFC-125	150,000	120,000	190,563	152,450
	PFC	7,500	0	50,625	0
Fire Protection: Streaming Agents	Halon 1211	189,000	132,300	111,419	78,035
	Halotron I	50,400	5,600	4,688	4,688
	HFC-236	12,600	12,600	36,016	36,016

Based on the bank estimates presented above, this analysis applies average equipment lifetimes to then estimate the quantities of chemical reaching EOL in each year, based on an assumed average lifetime of 20 years for total flooding equipment, and 12 years for streaming equipment. Therefore, each year, it is assumed that 5% of chemicals banked in the flooding sector (i.e., 1/20) and 8% of chemicals banked in the streaming sector (i.e., 1/12) will reach EOL. The resulting quantity of chemicals estimated to reach EOL in 2010 and 2020 are presented in Table V-3. As shown, all ODS banks in the fire protection sector are assumed to reach EOL by 2020.

Table V-3: Quantity of High-GWP Gases from Fire Protection Sector Reaching EOL in 2010 and 2020

Sector	System Type	Bank Size (lbs)		Bank Size (MTCO2 eq.)	
		2010	2020	2010	2020
Fire Protection: Flooding Agents	Halon 1301	15,000	0	46,960	0
	HFC-227ea	67,000	71,053	88,816	71,053
	HFC-125	7,500	7,623	9,528	7,623
	PFC	375	0	2,531	0
Fire Protection: Streaming Agents	Halon 1211	15,750	11,025	9,285	6,503
	Halotron I	4,200	4,200	391	391
	HFC-236	1,050	1,050	3,001	3,001

Existing high-GWP stockpiles from the solvents sector in California are believed to include CFC-113 from dry cleaning (for movie costumes and manufacturing of medical devices), as well as HCFC-141b for cleaning of electrical equipment. The GWPs and ODPs of these chemicals are presented below.

Table V-4: GWP and ODPs of Stockpiled ODS Solvents (IRTA)

Chemical	GWP	ODP
CFC-113	5,000	0.8
HCFC-141b	630	0.11

The estimated banks of these miscellaneous solvent stockpiles in 2010 are presented below, by ODS type and application. Because these banks consist of obsolete chemicals that may no longer be produced or imported, they are not expected to increase over time.

Table V-5: Existing High-GWP Stockpiles in California (IRTA 2010)

Sector	Chemical Type	Bank Size 2010	
		Lbs.	$MTCO_2eq$
Dry Cleaning	CFC-113	3,575	8,106.6
Medical Device Manufacturing	CFC-113	3,575	8,106.6
Electrical Equipment Cleaning	HCFC-141b	5,720	1,634.3
Total		12,870	17,847

V.4. Defining Business-As-Usual (BAU)

In the fire sector, there are established routes for managing high-GWP gases at equipment end of life (EOL). Moreover, such gases are valuable materials and are easily recycled or reclaimed for reuse.[94] Thus, current market conditions—in addition to environmental and legal concerns—are sufficient to encourage recovery and recycling at EOL, with little if any intentional venting expected from this sector.

Generally at EOL, decommissioned flooding/extinguishing containers are returned to the original equipment manufacture's specialist filling facility for recovery and subsequent reclamation/reuse. Across the United States, there are six companies that recycle one or more types of fire extinguishing agents. Three of the six recycling companies have facilities in California (IRTA 2010).

Conversely, the ultimate fates of stockpiled ODS solvents are highly uncertain. Legally, they may be kept in storage, sent for reclamation/reuse, or safely destroyed using approved technologies.[95]

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[94] Because the most common agents used and recovered in the fire suppression sector are pure substances and not a mixture, they are relatively easy to recover and recycle/reclaim. Moreover, given the high market value of halons and HFCs, there is incentive for individuals/companies to recycle/reclaim rather than to destroy recovered agent.

[95] Approved technologies for destroying ODS are presented in Annex II of the Report of the 15th Meeting of the Parties of the Montreal Protocol. For (dilute) ODS solvents, these technologies include: municipal solid waste incineration, and rotary kiln incineration. For (concentrated) ODS refrigerants and blowing agents, approved technologies include: cement kilns, liquid injection incineration, gaseous/fume oxidation, reactor cracking, rotary kiln incineration, argon plasma arc, inductively coupled

V.5. Key Assumptions

This section outlines the key basic assumptions used to estimating GHG emissions and costs.

For high-GWP gases banked in fire protection equipment and miscellaneous solvent stockpiles, each of the following emission impacts are evaluated:

- Avoided direct high-GWP gases emissions due to the recovery and destruction/reclamation of fire extinguishing agents at equipment EOL and ODS from miscellaneous solvent stockpiles;
- Indirect CO_2 and criteria air pollutant emissions associated with the energy consumed during the destruction and reclamation processes; and
- Indirect CO_2 and criteria air pollutant emissions associated with transport of high-GWP gases to a reclamation or destruction facility.

Furthermore, the following cost impacts are also evaluated:

- Costs associated with transporting high-GWP gases to a reclamation or destruction facility;
- Costs associated with labor time to handle high-GWP gases en route to a reclamation or destruction facility; and
- Costs associated with the energy consumed during the destruction and reclamation process ($/kWh).

No capital costs associated with recovery equipment or reclamation/destruction equipment is assumed in this analysis, given that existing infrastructure is in place.

Transport

ODS/GHGs may be transported to several locations following recovery before they are ultimately reclaimed or destroyed. For simplicity, this analysis only accounts for transportation of fire extinguishing agents and ODS from miscellaneous solvent stockpiles from one point of recovery/consolidation to the point of reclamation or destruction. To be consistent with previous LCA sections, this analysis assumes that average distance that agents and ODS from stockpiles must travel to reach a destruction facility is 750 miles, and 150 miles to reach a reclamation facility. Trucks are assumed to be 28-feet long with the capacity to transport 9,600 lbs of agent/ODS from stockpiles material per truckload. Trucks are assumed to make empty return trips in all scenarios. It is assumed that trucks travel at an average speed of 50 mph.

Energy Consumption

Based on confidential industry information, this analysis assumes that the average energy consumption per pound of fire extinguishing agent or ODS from stockpiles reclaimed is 1 kWh. The energy use for destroying these gases is assumed to be negligible, given that such destruction is likely to represent less than 0.01% of a destruction facility's (e.g., cement kiln's) input feed on any given day, and that the facility is likely to operate regardless of whether ODS/HFCs are destroyed or not (World Bank 2009).[96] Therefore, the costs and GHG emissions

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radio frequency plasma, microwave plasma, nitrogen plasma arc, gas phase catalytic dehalogenation, and superheated steam reactor.

[96] In the United States, only one of the 10 to 20 known destruction facilities that accept ODS for commercial destruction (a plasma arc facility) operates exclusively for the purpose of destroying ODS. However, this facility is likely to be used to destroy

associated with the energy consumed for destruction of extinguishing agents and ODS from stockpiles are not quantified in this analysis.

V.5.1. Estimating Emissions

Direct Emissions Avoidable

Direct GHG emission savings can be realized if fire extinguishing agents are recovered from equipment at EOL and then either reclaimed for reuse or safely destroyed. Emission savings can also be realized by safely destroying ODS from stockpiles. Consistent with IRTA (2011), this analysis assumes that 100% of the bank is recoverable, but that a 1% loss occurs during the recycling process (ITRA 2011).[97] Emission savings are estimated using the GWPs and ODPs presented in Table V-1 and Table V-4.

Indirect GHG and Criteria Pollutant Emissions from Transport

Indirect emissions of CO_2 and criteria pollutants associated with transport will vary based on the distances traveled for reclamation (150 miles) or destruction (750 miles). Table V-6 presents the assumed fuel efficiency of trucks carrying fire extinguishing agents/ODS from stockpiles sent for reclamation or destruction and the resulting emissions assumed per mile. Diesel fuel is assumed to have a lower heating value (LHV) of 135.5 MJ/gal and a CO_2eq emission factor of 94.7 g CO_2eq/MJ, based on GREET 1.8b used for the California Low Carbon Fuel Standard (ARB 2009c).[98]

Table V-6: Truck Fuel Efficiency and Emissions per Mile (kgCO_2eq/mile), Based on U.S. EPA's PERE-HD

Load	Quantity of High GWP Gas Per Truckload (lbs)	Total Truckload Cargo Weight (lbs)	Fuel Efficiency[a]	Emissions per Mile (kgCO_2eq/mile)
Misc. High-GWP Gases	9,600	12,000	7.2	1.78

[a] Fuel Efficiency is based on the U.S. EPA (2010) PERE-HD Calculator

Criteria pollutant emissions associated with transport are based on the emission factors presented in Table V-7, based on Façanha and Horvath (2007). It should be noted that criteria air pollutant emission factors reflect global emission estimates; due to analytical limitations, emissions for criteria air pollutants could not be disaggregated for California specific regions or air districts.

Table V-7: Criteria Pollutant Transport Emission Factors (g/mile)[a]

Load	NO_x	PM10	PM2.5	SO_2
Misc. High-GWP Gases	14.49	0.40	0..07	0.37

[a] Emission factors account for fuel combustion and pre-combustion.
Source: Façanha and Horvath (2007).

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halons, due to the technical concerns associated with destroying such agents in hazardous waste combustors. This facility is located in Ohio.

[97] Actual recovery efficiency is likely to be less than 100%. According to ICF (2010), the recovery efficiency for fire protection equipment is 96%.

[98] The CO_2eq emission factor for diesel fuel includes well to tank (WTT) and tank-to-wheel energy and greenhouse gas values and vehicle fuel emissions for California Ultra Low-Sulfur Diesel (ULSD).

Indirect Emissions from Energy Consumption

Table V-8 presents the emission factors used to calculate indirect GHG and criteria pollutant emissions associated with the energy consumed during the reclamation process.

Table V-8: Emission Factors Associated with Energy Consumption

Energy Consumption Emission Factors (g/kWh)				
g CO_2eq/kWh[a]	g NO_x/kWh	g PM10/kWh	g PM2.5/kWh	g SO_x/kWh
751.50	1.18	1.02	0.27	2.60

[a] The CO_2eq emission factor represents net CO_2, which includes CO_2, CO, and VOCs.
Source: GREET 1.8c.

V.5.2. Estimating Costs

In this analysis, the following annual costs and cost savings are quantified:

- Recovery costs
- Reclamation and destruction costs/savings
- Transport and labor costs
- Energy costs
- Capital equipment costs

The assumptions are described below.

Recovery

This analysis assumes a cost of $3.00/lb for high-GWP gas recovery/collection from fire extinguishing equipment and ODS from miscellaneous solvent stockpiles.

Reclamation and Destruction

Based on confidential industry information, this analysis assumes an average cost *savings* of $5.00/lb for fire extinguishing agents returned for reclamation. It should be noted, that any in-house reuse (recycling) of agent from decommissioned systems (i.e., without prior reclamation) will result in greater cost savings—on the order of $13 - $20/lb for the HFC agents, which is their estimated market values (IRTA 2011). The cost to destroy these agents is assumed to be $3.00/lb for destruction (TEAP 2009). This analysis assumes the same reclamation and destruction costs for ODS from stockpiles.

Transport and Labor

Costs associated with transporting ODS/HFCs to a destruction facility can vary greatly depending on distance and quantity, and whether the transport is within or beyond state borders. For this analysis, transport costs are estimated based on fuel and labor costs. To be consistent with the other LCA analyses in this report, a fuel cost of $0.01 per lb. and a labor cost of $0.05/lb for high-GWP gas sent for reclamation is assumed. A fuel cost of $0.05/lb and labor cost of $0.23/lb is assumed for chemical sent for destruction.

Energy

Costs associated with the energy consumed during both the destruction and reclamation process is based on an estimated electricity cost of $0.11/kWh.

Capital Equipment

No capital costs are assumed in this analysis, as infrastructure is already in place (i.e., recovery equipment, reclamation facilities, and destruction facilities).

V.6. Costs and Benefits

This section presents the estimated costs and benefits associated with the recovery and reclamation or destruction of high-GWP gases from fire extinguishing equipment and miscellaneous solvent stockpiles. Cost-effectiveness is also presented in terms of $/MTCO$_2$eq.

V.6.1. Costs

Potential costs associated with recovery and subsequent reclamation or destruction of fire extinguishing agents from both the flooding and streaming sectors are presented in Table V-9 and Table V-11, respectively. The potential costs associated with recovery and subsequent reclamation or destruction of ODS from stockpiles are presented in Table V-11. An annual discount rate of 5% is applied. This discount rate was chosen for consistency with other ARB analyses.

Table V-9: Total Estimated Costs for Recovery, Reclamation and Destruction of Flooding Agents[a]

Year	Agent Recovery	Recovery and Reclamation				Recovery and Destruction		
		Energy Consumption	Transport (Labor & Fuel)	Value of Used Agent (Cost Savings)	Net Cost Savings	Transport (Labor & Fuel)	Agent Destruction	Net Cost
2010	$271,125	$9,941	$5,056	$451,875	($165,753)	$25,281	$271,125	$567,531
2020	$236,025	$8,654	$4,402	$393,376	($144,294)	$22,008	$236,025	$494,059
2010–2020 (NPV)	$2,120,457	$77,750	$39,544	$3,534,096	($1,296,344)	$197,720	$2,120,457	$4,438,635

[a] Total costs for ODS, HFC and PFC combined.

Table V-10: Total Estimated Costs for Recovery, Reclamation and Destruction of Streaming Agents[a]

Year	Agent Recovery	Recovery and Reclamation				Recovery and Destruction		
		Energy Consumption	Transport (Labor & Fuel)	Value of Used Agent (Cost Savings)	Net Cost Savings	Transport (Labor & Fuel)	Agent Destruction	Net Cost
2010	$63,000	$2,310	$1,175	$105,000	($38,515)	$5,874	$63,000	$131,874
2020	$48,825	$1,790	$911	$81,375	($29,849)	$4,553	$48,825	$102,203
2010-2020 (NPV)	$470,149	$17,239	$8,768	$783,582	($287,426)	$43,839	$470,149	$984,138

[a] Total costs for ODS, HFC, and PFC combined.

Table V-11: Total Estimated Costs for Reclamation and Destruction of ODS from Solvent Stockpiles

Year	ODS from Stockpiles Recovery	Reclamation				Destruction		
		Energy Consumption	Transport (Labor & Fuel)	Value of Used Agent (Cost Savings)	Net Cost Savings	Transport (Labor & Fuel)	Agent Destruction	Net Cost
2010	$38,610	$1,416	$720	$64,350	$23,604	$3,600	$38,610	$80,820
2020	—	—	—	—	—	—	—	—
2010–2020 (NPV)	$175,928	$6,451	$3,281	$293,213	$107,554	$16,404	$175,928	$368,259

V.6.2. Benefits

The GHG emissions savings potential associated with the recovery and subsequent reclamation or destruction of fire extinguishing agents by type are shown in Table V-12 and Table V-13. The potential GHG emission savings potential associated with the reclamation or destruction of ODS from stockpiles are presented in Table V-14. The GHG emissions savings potential by source is shown graphically in Figure V-1.

Table V-12: Estimated GHG Benefits Associated with Flooding Agents (MTCO$_2$eq)

Year	Direct GHG Emissions Avoidable from Agent Recovery / Destruction		Direct GHG Emissions Avoidable from Agent Recovery / Reclamation[b]		Recovery and Reclamation[a]			Recovery and Destruction[a]		
	ODS	HFCs & PFCs	ODS	HFCs & PFCs	Indirect GHG Emissions from Energy Consumption	Indirect GHG Emissions from Transport	Net GHG Emissions Avoided	Indirect GHG Emissions from Energy Consumption	Indirect GHG Emissions from Transport	Net GHG Emissions Avoided
2010	46,960	100,875	46,490	99,866	68	3	146,287	NA	13	147,823
2020	—	78,657	—	77,888	59	2	77,827	NA	11	78,664
Total (2010–2020)	258,280	987,527	255,697	977,652	698	26	1,232,625	NA	129	1,245,678

NA= Not applicable; the energy use for destroying high-GWP gas is assumed to be negligible, given that high-GWP gas destruction is likely to represent a maximum of 0.01% of a destruction facility's (e.g., cement kiln's) input feed on any given day, and that the facility is likely to operate regardless of whether ODS is destroyed or not (World Bank 2009).

[a] Total GHG benefits for ODS and HFC combined.

[b] This analysis assumes a 1% loss during the reclamation process.

Table V-13: Estimated GHG Benefits Associated with Streaming Agents (MTCO$_2$eq)

Year	Direct GHG Emissions Avoidable from Agent Recovery / Destruction		Direct GHG Emissions Avoidable from Agent Recovery / Reclamation[b]		Recovery and Reclamation[a]			Recovery and Destruction[a]		
	ODS	HFCs	ODS	HFCs	Indirect GHG Emissions from Energy Consumption	Indirect GHG Emissions from Transport	Net GHG Emissions Avoided	Indirect GHG Emissions from Energy Consumption	Indirect GHG Emissions from Transport	Net GHG Emissions Avoided
2010	9,676	3,001	9,579	2,971	16	1	12,534	NA	3	12,674
2020	6,894	3,001	6,825	2,971	12	<1	9,783	NA	2	9,893
Total (2010–2020)	91,130	33,015	90,219	32,685	154	6	122,744	NA	29	124,117

NA= Not applicable; the energy use for destroying high-GWP gas is assumed to be negligible, given that high-GWP gas destruction is likely to represent a maximum of 0.01% of a destruction facility's (e.g., cement kiln's) input feed on any given day, and that the facility is likely to operate regardless of whether ODS is destroyed or not (World Bank 2009).

[a] Total GHG benefits for ODS and HFC combined.

[b] This analysis assumes a 1% loss during the reclamation process.

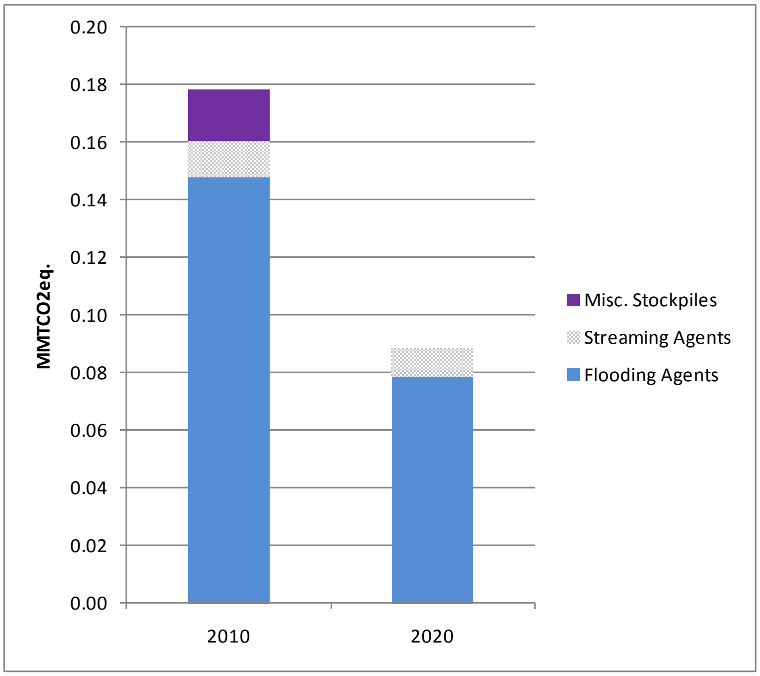
Table V-14: Estimated GHG Benefits Associated with ODS from Solvent Stockpiles ($MTCO_2eq$)

Year	Direct GHG Emissions Avoidable from ODS Recovery & Treatment		Recovery and Reclamation[a]			Recovery and Destruction		
	Destruction	Reclamation[a]	Indirect GHG Emissions from Energy Consumption	Indirect GHG Emissions from Transport	Net GHG Emissions Avoided	Indirect GHG Emissions from Energy Consumption	Indirect GHG Emissions from Transport	Net GHG Emissions Avoided
2010	17,847	17,669	10	<1	17,659	—	2	17,846
2020	—	—	—	—	—	—	—	—
Total (2010–2020)	98,161	97,179	53	2	97,124	—	10	98,151

NA= Not applicable; the energy use for destroying high-GWP gas is assumed to be negligible, given that high-GWP gas destruction is likely to represent less than 0.01% of a destruction facility's (e.g., cement kiln's) input feed on any given day, and that the facility is likely to operate regardless of whether ODS is destroyed or not (World Bank 2009).

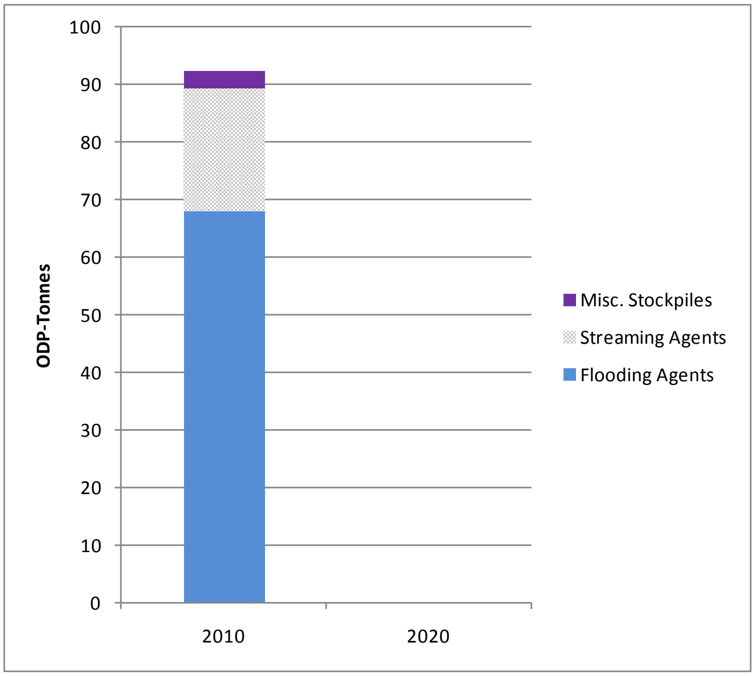
[a] This analysis assumes a 1% loss during the reclamation process.

Figure V-1: Potential Emissions Savings by Source (MMTCO$_2$eq)



In addition to the GHG benefits presented above, stratospheric ozone benefits will also result, as summarized in Figure V-2. It should be noted that no ozone benefits are assumed to be realized in 2020, as all ODS-containing fire extinguishing equipment is assumed to have already reached EOL.

Figure V-2: Potential Emissions Savings by Source through 2020 (ODP-tons)



While environmental benefits are associated with fire extinguishing agent recovery and subsequent reclamation or destruction at equipment EOL, and reclamation/destruction of ODS from solvent stockpiles, slight environmental disbenefits result from an increase in criteria pollutant emissions associated with additional transport requirements for reclamation and destruction, as presented in Table V-15 and Table V-16.

Table V-15: Estimated Criteria Pollutant Emissions (MT) Associated with Reclamation

Year	Flooding Agents				Streaming Agents				ODS Stockpiles			
	NO_x	SO_x	PM10	PM2.5	NO_x	SO_x	PM10	PM2.5	NO_x	SO_x	PM10	PM2.5
2010	0.0205	0.0005	0.0006	0.0001	0.0048	0.0001	0.0001	<0.0001	0.00029	0.0001	0.0001	<0.0001
2020	0.0178	0.0005	0.0005	0.0001	0.0037	0.0001	0.0001	<0.0001	—	—	—	—
2010–2020	0.2105	0.0054	0.0058	0.0010	0.0464	0.0012	0.0013	0.0002	0.0160	0.0004	0.0004	0.0001

Table V-16: Estimated Criteria Pollutant Emissions (MT) Associated with Destruction

Year	Flooding Agents				Streaming Agents				ODS Stockpiles			
	NO_x	SO_x	PM10	PM2.5	NO_x	SO_x	PM10	PM2.5	NO_x	SO_x	PM10	PM2.5
2010	0.1023	0.0026	0.0028	0.0005	0.0238	0.0006	0.0007	0.0001	0.0146	0.0004	0.0004	0.0001
2020	0.0891	0.0023	0.0025	0.0004	0.0184	0.0005	0.0005	0.0001	—	—	—	—
2010–2020	1.0525	0.0269	0.0291	0.0051	0.2321	0.0059	0.0064	0.011	0.0801	0.0022	0.0022	0.0004

Cost Effectiveness

The incremental costs per GHG emission reduction associated with proper management of retired fire protection equipment and ODS from solvent stockpiles are presented in Table V-17, Table V-18, and Table V-19, as well as the associated net present values (assuming a 5% discount rate). While this analysis does not vary costs by year or chemical type, actual benefits will vary based on the mix of chemicals projected to be available for recycling/reclamation/destruction over time. As shown, for flooding agents, the annual cost effectiveness for ODS, HFC, and PFC combined varies from a cost savings of approximately \$1MTCO$_2$eq for recovery/reclamation (due to the value of returned used agent) to a cost of over \$3.50/MTCO$_2$eq for recovery/destruction. For streaming agents, the annual cost effectiveness for ODS and HFC combined ranges from a cost savings of over \$2/MTCO$_2$eq for recovery/reclamation, to a cost of nearly \$8/MTCO$_2$eq for recovery/destruction. For ODS from stockpiles, the annual cost effectiveness ranges from a cost savings of over \$1/MTCO$_2$eq to a cost of \$3.75/ MTCO$_2$eq for recovery/destruction.

Table V-17: Flooding Agents: Incremental \$/MTCO$_2$eq 2010–2020

Year	ODS			HFC & PFC			Total (ODS + HFC + PFC)		
	Recovery	Recovery/ Reclamation*	Recovery/ Destruction	Recovery	Recovery/ Reclamation*	Recovery/ Destruction	Recovery	Recovery/ Reclamation*	Recovery/ Destruction
2010	$0.96	*($0.59)*	$2.01	$2.24	*($1.39)*	$4.69	$1.83	*($1.13)*	$3.84
2020	—	—	—	$3.00	*($1.85)*	$6.28	$3.00	*($1.85)*	$6.28
2010–2020 NPV	$0.79	*($0.49)*	$1.66	$1.94	*($1.20)*	$4.06	$1.70	*($1.05)*	$3.56

* Values in parentheses denote cost *savings*.

Table V-18: Streaming Agents: Incremental \$/MTCO$_2$eq 2010–2020

Year	ODS			HFC & PFC			Total (ODS + HFC + PFC)		
	Recovery	Recovery/ Reclamation*	Recovery/ Destruction	Recovery	Recovery/ Reclamation*	Recovery/ Destruction	Recovery	Recovery/ Reclamation*	Recovery/ Destruction
2010	$6.19	*($3.83)*	$12.95	$1.05	*($0.65)*	$2.20	$4.97	*($3.07)*	$10.41
2020	$6.63	*($4.10)*	$13.87	$1.05	*($0.65)*	$2.20	$4.97	*($3.07)*	$10.41
2010–2020 NPV	$4.87	*($3.01)*	$10.20	$0.79	*($0.49)*	$1.66	$3.79	*($2.34)*	$7.93

* Values in parentheses denote cost *savings*.

Table V-19: ODS Stockpiles: Incremental \$/MTCO$_2$eq 2010–2020

Year	ODS		
	Recovery	Recovery/ Reclamation*	Recovery/ Destruction
2010	$2.16	*($1.34)*	$4.53
2020	—	—	—
2010–2020 NPV	$1.79	*($1.11)*	$3.75

* Values in parentheses denote cost *savings*.

V.7. Discussion of Findings

Table V-20 summarizes the estimated total costs and GHG emissions avoided by source from 2010 to 2020.

Table V-20: Total Incremental Costs and GHG Emissions Avoided by Source (2010-2020)[a, b]

Total Costs and GHG Emissions Avoided	Flooding Agents	Streaming Agents	ODS Stockpiles
Emissions Avoided from Recovery ($MTCO_2eq$)	1,245,807	124,145	98,161
Emissions Avoided from Recovery (ODP-tons)	374	118	16
Cost of Recovery ($ million)	2.1	0.47	0.18
Cost Savings of Recovery and Reclamation ($ million)	1.3	0.29	0.11
Cost of Recovery and Destruction ($ million)	4.4	1.0	0.37

[a] Total for ODS, HFC, and PFC combined.

Agent/stockpile recovery can result in GHG emission savings of 1,468,113 $MTCO_2eq$ from 2010 through 2020. Of the sources reviewed in this analysis, recovery at equipment EOL is most critical from the flooding sector, as this end-use is projected to have the greatest share of agent installed in equipment expected to reach EOL through 2020. It is expected that the majority of these emissions will be avoided in the BAU through proper recovery and reuse of high-GWP gases.

V.7.1. Scope of Work Limitations

A number of high-GWP chemicals were not included within the scope of this study. These chemicals are described below.

Aerosol Propellants in Consumer Products

High-GWP chemicals used as aerosol propellants in consumer products have historically been a significant source of ODS and GHG emissions. However, consumer products were not included in the IRTA 2011 study or in this LCA, because consumer products are assumed to be used in the year in which they were purchased, with no significant stockpiled amounts of high-GWP chemicals available for recovery and destruction. Additionally, aerosol propellants have increasingly become a less significant source of GHG emissions, with the commonly used CFC propellants CFC-11 and CFC-12 (GWPs of 3800 and 8100) replaced in 1995 by lower-GWP propellants. Currently, 95 percent of aerosol propellants are comprised of very low-global warming chemicals (carbon dioxide, hydrocarbons, dimethyl ether, carbon dioxide, and nitrogen; with GWPs ranging from 1 – 11), with the remaining five percent using HFC-134a (GWP 1300) or HFC-152a (GWP 140). (ARAP 2007). Based on scaling U.S. EPA Vintaging Model national emissions data to the California population, it is estimated that 2010 GHG emissions from aerosol propellants are 1.52 $MMTCO_2E$ (all HFC, no ODS), and increasing to 1.86 $MMTCO_2E$ annually by 2020 unless lower-GWP propellants replace HFC-134a and HFC-152a (U.S. EPA, 2008). Although a detailed analysis of historical GHG emissions from aerosol propellants was not conducted for this LCA, it would be reasonable to estimate that because 95 percent of aerosol propellants currently used are very low-GWP, the GHG emissions from this source are likely to have decreased by as much as 95 percent since 1995, when CFC propellants were banned.

Non-ODS Solvents

As described in the introduction, high-GWP solvents are used in various applications, including vapor degreasing; disk lubing; and cleaning energized electrical equipment, film, and fabric. ODS solvents are CFCs or HCFCs that are no longer manufactured and are stock-piled for specific niche uses. This LCA covers ODS solvents because the stock-piled amounts can be recovered and destroyed, thus permanently reducing the potential emission source. However, non-ODS solvents with relatively high GWPs continue to be manufactured, therefore, any recovery and destruction of these solvents becomes a moot point, as additional solvent can simply be manufactured to take its place – resulting in a zero sum gain of net emissions reduction. (Unlike refrigerants or foam expansion agents remaining in equipment at end-of-life, stockpiled solvents are not considered waste products.) Therefore, non-ODS solvents are not covered in this LCA for recovery and destruction cost-benefit, although the following includes a brief summary of potential emissions from non-ODS solvents.

Greenhouse gas emissions from non-ODS solvents are relatively insignificant, estimated at 0.010 $MMTCO_2E$ in 2010, and expected to increase slightly to 0.014 $MMTCO_2E$ annually by 2020. (IRTA, 2011). (For comparison with ODS solvents, it is estimated that in 2010, ODS solvent emissions were 0.018 $MMTCO_2E$, which will diminish to zero emissions by 2020 as the stockpiled ODS solvent is used.) The most common non-ODS solvents in use (with relatively high-GWPs) are HFC-43-10mee (GWP of 1300), HFC-365mfc (GWP of 890), PFC-51-14 (GWP of 7400), and various hydrofluoroethers (HFEs), including HFE-347pcf, HFE-449s1 (or HFE-7100), and HFE-569sf2 (or HFE-7200) (with GWPs respectively of 580, 320, and 55). (IPCC/TEAP, 2005; and Owens, 2000).

Additionally, many non-ODS, low-GWP solvents are currently in use, and these consist mainly of hydrocarbon blends. These low-GWP solvents are of interest as sources of volatile organic compound (VOC) emissions, but are not within the scope of work in the context of this high-GWP GHG study.

Sulfur Hexafluoride (SF_6)

Sulfur hexafluoride (SF_6) has a GWP of 23,900, and is potentially a significant source of GHG emissions. SF_6 was not included in this LCA because it has been adequately inventoried and analyzed by other ARB research projects, as described in project information presented in the ARB website at: http://www.arb.ca.gov/cc/ghgsectors/ghgsectors.htm (under section “High Global Warming Potential [GWP])”.

V.8. Recommendations

The potential GHG emissions from high-GWP gases banked in the fire protection sector in California are relatively small—estimated at roughly 160,512 $MTCO_2eq$ in 2010 and 88,570 $MTCO_2eq$ in 2020. Moreover, these gases are likely to be managed properly at equipment EOL as the industry is small and specialized, with well-established routes for chemicals management already in place, as well as market drivers to compel agent recovery/reuse. However, given the negative cost drivers associated with recovery and destruction of F-gases, ARB could consider additional market-based mechanisms to promote the destruction of these gases in lieu of reuse (e.g., a tradable credit/certificate system); this may be desirable for ODS that can no longer be produced or imported and are not required for critical uses.

Potential emissions of high-GWP gases banked in California stockpiles are yet smaller than those in the fire protection sector. This analysis shows that the recovery and reclamation/destruction of these chemicals can be done at negative or low cost, on a $MTCO_2eq$-basis; however, given the potentially dispersed nature of the stockpiles and the relatively small quantities owned by individuals, additional efforts could be considered to educate and compel stockpile owners to reclaim or destroy these materials. Thus, the ARB could consider stakeholder outreach, economic incentives, or other programs (e.g., take-back programs) to better ensure that high-GWP obsolete chemicals are not kept indefinitely in storage—where they could slowly leak over time—or worse, be vented to the atmosphere.

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V.9. Appendix: Report Figures presented as Data

The following tables show the data which ICF used to develop the figures and graphs used throughout Part V. LCA on Fire Extinguishing Agents and Other Miscellaneous ODS / High-GWP . In each case, numbered tables are followed by a Figure reference in brackets (from Figure V-xx), and the title of the relevant figure as it is shown in the body of the report.

Table V-21 (from Figure V-1): Potential Emissions Savings by Source (MMTCO$_2$eq)

Source	Projected Emissions (MMTCO$_2$eq)	
	2010	2020
Misc. Stockpiles	0.018	—
Streaming Agents	0.15	0.12
Flooding Agents	2.96	1.57

Table V-22: (from Figure V-2): Potential Emissions Savings by Source through 2020 (ODP-tons)

Source	Projected Emissions (ODP tons)	
	2010	2020
Misc. Stockpiles	2.9	—
Streaming Agents	21	—
Flooding Agents	68	—

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VI. Glossary of Terms

AB	Assembly Bill
AB 32	California Global Warming Solutions Act of 2006
AC	Air conditioner
ADC	Alternative Daily Cover
AHAM	Association of Home Appliance Manufacturers
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
AR4	Fourth Assessment Report (of the Intergovernmental Panel on Climate Change)
ARB	(California) Air Resources Board
ARCA	Appliance Recycling Centers of America, Inc.
ASR	Auto Shredder Residue
BAU	Business as usual
CAR	Certified Appliance Recycler
C&D	Construction and Demolition
CFC	Chlorofluorocarbon
CFR	Code of Federal Regulations
CH_4	Methane
CIWMB	California Integrated Waste Management Board (1987-2009), currently CalRecycle
CO	Carbon monoxide
CO_2	Carbon dioxide
CPUC	California Public Utilities Commission
DAR	Dedicated Appliance Recycling Facility
DOE	(United States) Department of Energy
DIYer	Do-it-Yourselfer
DRE	Destruction and Recovery Efficiency
DSM	Demand-side management
DTSC	Department of Toxic Substances Control
EIA	Energy Information Administration
EOL	End-of-Life
EPA	(United States) Environmental Protection Agency
GHG	Greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation model
GWP	Global warming potential
HARDI	Heating, Airconditioning, and Refrigeration Distributors International
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFE	Hydrofluoroether
HFO	Hydrofluoro-olefin
ISO	International Organization for Standardization

ISOR	Initial Statement of Reasons (for proposed regulation)
ISRI	Institute of Scrap Recycling Industries, Inc.
kW	Kilowatt
kWh	Kilowatt-Hour
LCA	Lifecycle Analysis
LHV	Lower-Heating Value
MLS	Multilateral Fund
MT	Metric ton (1,000 kilograms)
$MTCO_2eq$	Metric ton of carbon dioxide equivalent
$MMTCO_2eq$	Million metric tons of carbon dioxide equivalent
MRSH	Materials that Require Special Handling
MSW	Municipal Solid Waste
MVAC	Motor vehicle air conditioner
NOx	Oxides of nitrogen as nitrogen dioxide
NPV	Net present value
ODP	Ozone depletion potential
ODS	Ozone depleting substance
PCB	Polychlorinated biphenyl
PIR	Polyisocyanurate board stock
$PM_{2.5}$	Particulate matter with an aerodynamic diameter of 2.5 microns or less
PM_{10}	Particulate matter with an aerodynamic diameter of 10 microns or less
PU	Polyurethane insulating foam
psig	Pounds per square inch gauge
R-404A	Refrigerant blend 404A
R-410A	Refrigerant blend 410A
RMP	Refrigerant Management Program (of the California Air Resources Board)
RTOC	Refrigeration, Air Conditioning, and Heat Pumps Technical Options Committee
SAR	Second Assessment Report (of the Intergovernmental Panel on Climate Change)
SOx	Oxides of sulfur as sulfur dioxide
TAR	Third Assessment Report (of the Intergovernmental Panel on Climate Change)
TEAP	Technology and Economic Assessment Panel
UNEP	United Nations Environment Programme
VOC	Volatile Organic Compound
WTE	Waste-to-Energy
XPS	Extruded Polystyrene board stock